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DEPARTMENT OF THE NAVY
BUREAU OF SHIPS

RELIABILITY AND MAINTAINABILITY TRAINING HANDBOOK

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BUREAU OF SHIPS

RELIABILITY & MAINTAINABILITY TRAINING HANDBOOK

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PREFACE

This text, and the Bureau of Ships courses that use it, represents a substantial departure from the content of Reliability, Maintainability, and System Effectiveness texts and courses currently available. The departure is necessitated by specific BuShips management and technical needs, by significant omissions in previously available material, and by the current dynamic growth of the technology. Here are the principal considerations:

1. The point of view and language is for those who deal with contractors, as well as those in BuShips who must design for the required reliability and maintainability.

2. The text fully recognizes the current limitations of the "MTBF" approach, particularly for structural components, but also for many mechanical and electronic components. However, it presents the other approaches available for quantitative treatment.

3. Quite a few techniques that do not appear in government specifications, but which industry has found effective, are presented.

4. Emphasis is placed on (a) contract management, and (b) methods to design for required reliability, rather than just predict, "control" and measure it, as is common in other courses.

5. Reliability and maintainability are treated together wherever they are logically managed, designed, or analyzed together.

6. While the text content includes more "system effectiveness" than some courses by that name, it concentrates on just the reliability and maintainability contributions to system effectiveness, to avoid dilution.

7. Cost-effectiveness analysis approaches, to determine economically-achievable reliability and maintainability, are presented in some detail.

8. Shipbuilding and ships GFE and CFE examples are used wherever the information was obtainable, and shipbuilding critique obtained on all text.

Although the great majority of the techniques presented are well-established and proven, some are still controversial, and some are simply recommended on the basis of industry experience. This is to be expected of any fast-developing technology. In each case the text words will usually indicate such status.

For BuShips top management courses, Chapters 1, 2, 24, 25, and 26 are used, with a short condensation of Chapters 3 through 23. For middle management the condensation is much deeper. For the Technical Codes nearly all chapters are used in detail.

In order to achieve the above objectives several approaches have been used. Some excellent contributions have been used directly with little or no modification. Much material of significant content has been rewritten in more communicative language. About a third or more of the material is original with the authors. BuShips code 609.2 and the author would indeed appreciate receiving any recommendations for improvement, corrections, or criticisms of the text. It will have to be updated as the technology moves ahead.

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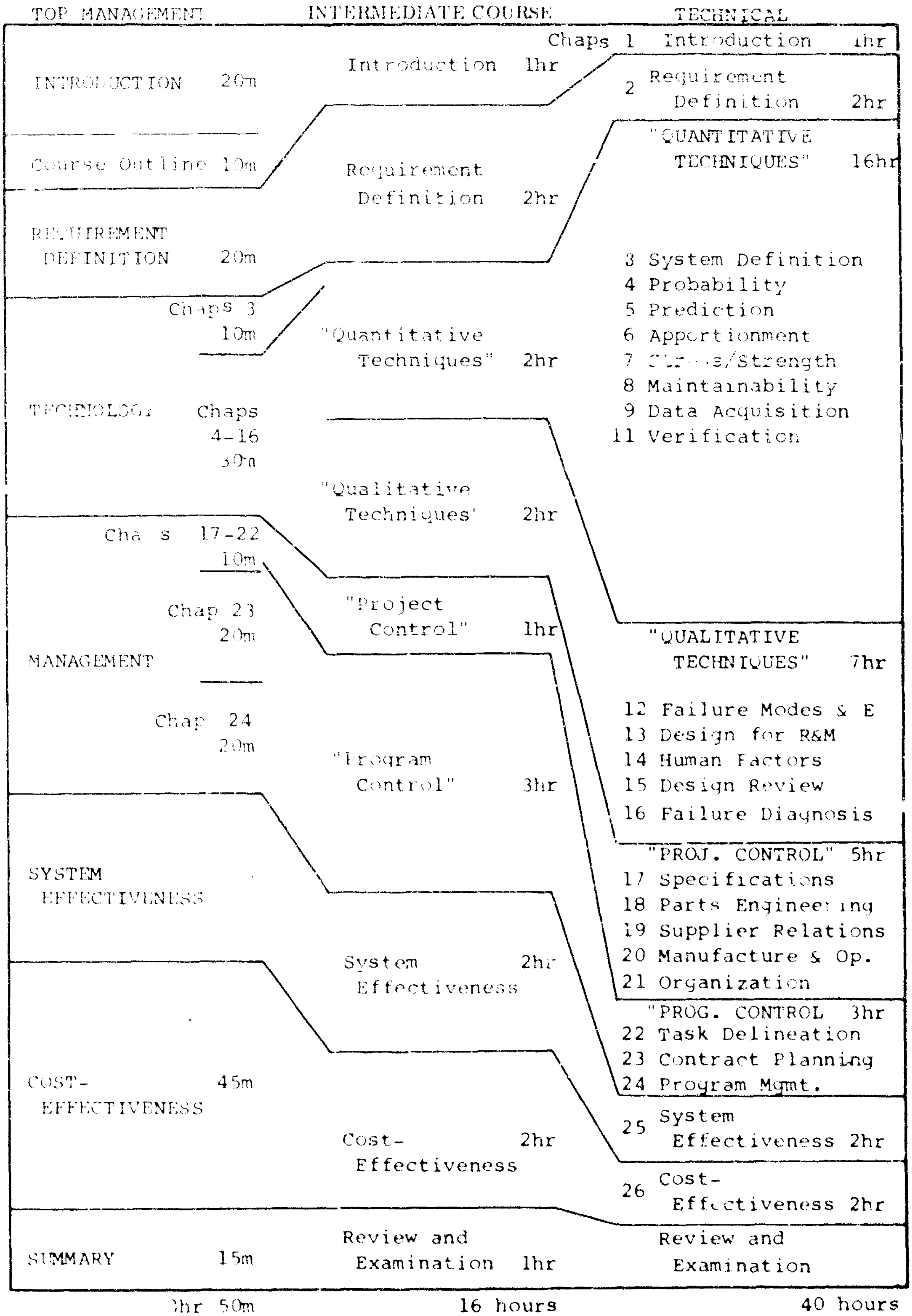
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A MESSAGE FROM THE CHIEF OF THE BUREAU OF SHIPS

Twenty-five years ago this month, when the Bureau was formed, we assumed the task of providing technical support to the Navy's forces at sea.

The Bureau of Ships is essentially an engineering organization, with military and civilian personnel alike schooled in the engineering disciplines necessary to the design, construction, and maintenance of modern naval ships. The history of the Bureau of Ships has been a history of talented individuals striving together to build a better Navy.

It is gratifying to contemplate the Bureau's past achievements, but it is the future that now occupies our minds and will engage our energies. As we celebrate the 25th anniversary of the Bureau of Ships, we face the future confidently. As we move into our second quarter-century, in this era of technological revolution, we realize that the tasks ahead will not be easy, but the men and women of the Bureau of Ships organization have demonstrated the ability to provide needed support to our great Navy by overcoming tremendous challenges in the past. We are confident that this tradition will endure and that our next twenty-five years, or next hundred years, will still find the talented individuals of the Bureau of Ships striving together to build a better Navy.

CHIEFS OF THE BUREAU OF SHIPS

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(LATER ADMIRAL)
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29 April 1963 –

BUREAU OF SHIPS
TWENTY-FIFTH
ANNIVERSARY

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USS LONGBEACH
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Chapter 1

INTRODUCTION

Chapter 1

INTRODUCTION

To talk Reliability to the Bureau of Ships might appear to be a little like "bringing coals to New Castle". The endurance of the ships you have designed and were responsible for building is traditional. Ships are reliable, they respond to the demand when required - get underway, proceed and complete an assignment and return. The country gives you credit. Innovations in shipbuilding you have taken in stride - the Nautilus, the George Washington, the Enterprise. These greats are testimonial to your competency in staying abreast of the new technologies.

1. STATEMENT OF THE PROBLEM

1.1 RELIABILITY OF EQUIPMENT

Then why talk reliability? The reliability we will be talking about is the reliability of equipment installed in your ships. You'll recognize that some of the equipment furnished by the Bureau and carried in these ships does cause the operating forces problems. Breakdowns of machinery have always occurred. It was not, in the old days, too frequently to be acceptable. Today the operating forces say that the difficulty of maintenance is no longer acceptable.

The Commander In Chief-Pacific Fleet recently said:

> "The ever-increasing complexity of shipboard equipment continues to add to the already overextended training requirements. The acceptance of shipboard equipment which exceeds the capabilities of Navy personnel to maintain can only result in a loss of fleet readiness."

The Commander In Chief-Atlantic Fleet seconded this:

> "Our Fleet is becoming so saturated in complexity that I have a mortal fear we may be blindly sailing on a collision course with something dreadful--like not being able to take the Fleet to sea and fight!"

R. Adm. J. O. Cobb, Asst. Chief of Naval Personnel, (1) stated:

> "The buying of complex systems which generate more and more requirements for skilled people we do not have, leads to an obvious conclusion, a lot of hardware goes begging for

maintenance and is not performing to its design potential. The Navy must necessarily suffer from this in the form of reduced readiness and ultimately, if the trend continues, an inability to carry out its mission."

1.2 RELIABILITY VS. COMPLEXITY

You'll recognize that the equipment I'm talking about is largely (but not entirely) electronics. The new technologies are largely made possible by electronics. Twenty years ago the title RADAR was declassified from SECRET. Twenty five years ago it wasn't even developed adequately to place aboard ship. In the last twenty-five years we have seen electronics on board ship mushroom from a small shack behind the pilot hourse to spaces filled with consoles, a complex array of antennas, RADAR, SONAR, TACAN, LORAN and so forth. Weaponry and defense have advanced to higher speeds, greater precision, immensely shortened reaction times.

The trend of the advancing technology is shown in Figure 1-4. Of particular interest is the gradual increase of installed electric power capacity. Figure 1-5 shows weapons trends for the same destroyers. You can note the specialization toward Anti-Aircraft warfare after World War I, then toward both Anti-Aircraft and Anti-Submarine warfare after World War II. Looking at Figure 1-6, we can see the impact of the electronics expansion on the Destroyer Classes, increases in weight, space, power required and cost. The major problem the operating forces find is a decreasing ability to keep the exotic new systems functioning.

Concurrently, there has been a trend in mechanical equipment toward higher power, greater speed of rotation, higher temperatures and pressures, less weight.

This trend in increased capability (more complexity in electronics, greater specific performance in mechanical areas) has taken its toll by increasing the cost and difficulty of maintenance and reducing the effectiveness of the Navy. This is why Admiral Schoech said in November (7).

> "System Effectiveness, and its fiscal corrollary cost effectiveness, constitute the most important single concern of military R&D Management."

1.3 RELIABILITY AS A MANAGEMENT PROBLEM

Obviously, we can't go back to the good old days. The new capabilities are necessary. Our effort must be to meet the challenge by learning to develop systems that meet the present day requirements of dependability, while staying abreast of our

DESTROYER CLASS TRENDS

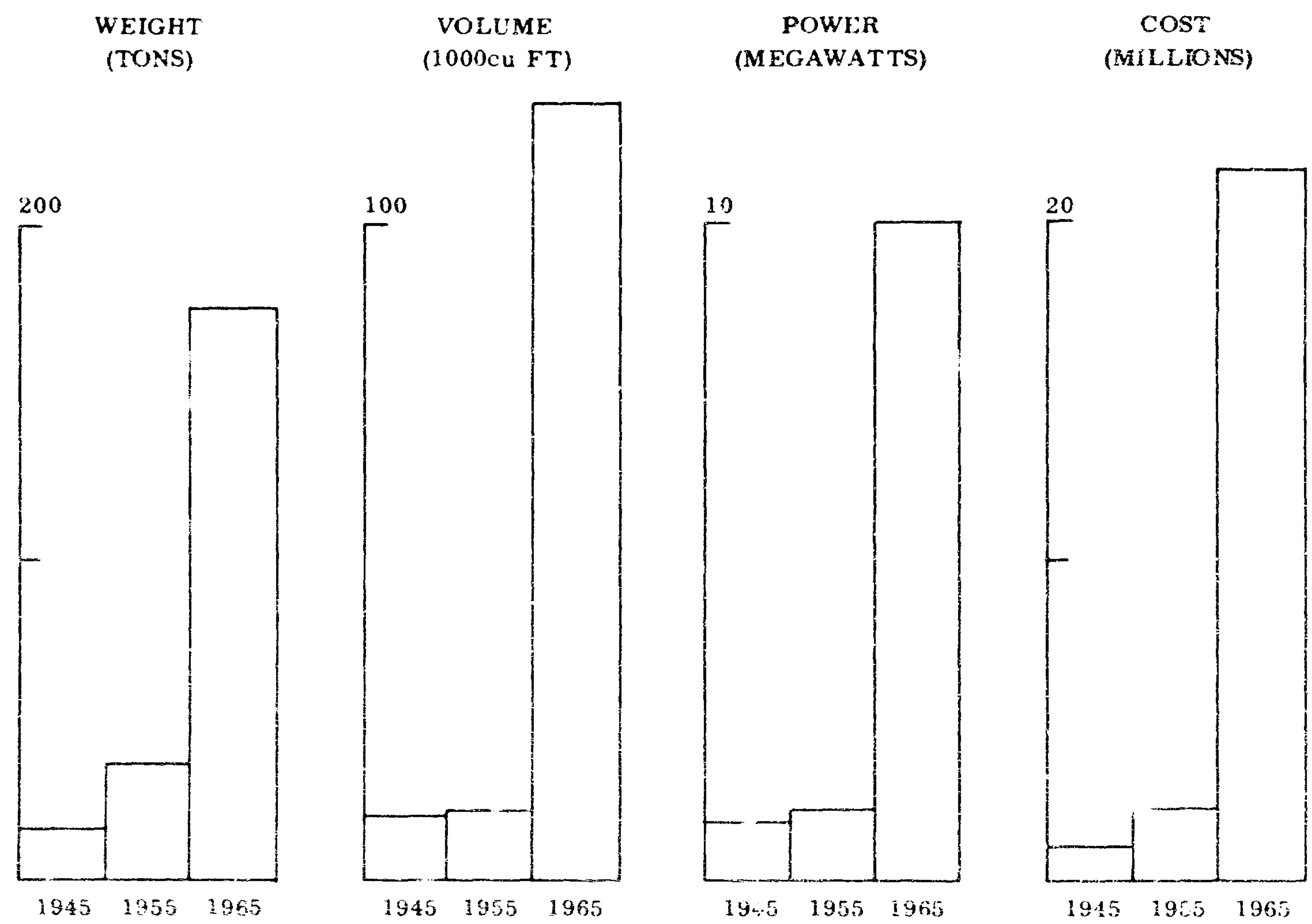
CLASS	STANDARD DISPLACEMENT	SHAFT HORSEPOWER	ELECTRIC POWER (KW)	CREW	PERIOD
DD1 BAINBRIDGE	420	8000	5	72	1900
DD348 FARRAGUT	1365	42,000	354	171	WW 1
DD356 PORTER	1850	50,000	400	225	POST WAR
DD573 HARRISON	2100	60,000	500	249	POST WAR
DD692 SUMNER	2200	60,000	800	325	WW 1
DL2 MITSCHER (EX DD 927)	3500	80,000	2000	374	POST WAR CONV 1951
DLG6 FARRAGUT (ORIG - DD)	4150	85,000	3000	359	1956
DLG26 BELKNAP	5340	85,000	6000	387	1961

DESTROYER CLASS ARMAMENT TRENDS

	MAIN BATTERY	SECONDARY BATTERY	TORPEDO TUBES	AA PROTECTION AS PROJECTILES
DD1 BAINBRIDGE	2-12PDR	5-6PDR	2-18"	
DD348 FARRAGUT	5-5"/38		2-21" QUAD	
DD573 PORTER	8-5"/38		2-21" QUAD	
DD573 HARRISON	5-5"/38	6-40MM	1-21" QUINT	HEDGEHOG-D. C. -ASW TORPEDOS
DD692 SUMNER	6-5"/38	10-40MM	2-21" QUINT	HEDGEHOG-D. C. -ASW TORPEDOS
DL2 MITSCHER	2-5"/54	4-3"/70	4-FIXED	4MK31-2MK108 ASW
DLG6 FARRAGUT	1-5"/54	4-3"/70	2-21" TRIP	TERRIER-ASROC-HEDGEHOG-MKIII
DLG26 BELKNAP	1-5"/54	2-3"/50	2-MK 25 2-21" TRIP	TERRIER-ASROC-DASH

ELECTRONIC EQUIPMENT TRENDS

DESTROYER CLASS



fleets needs in specific performance.

In an attempt to reverse the trend towards higher costs and reduced effectiveness--to get action started toward a major improvement in reliability and maintainability of Weapons Systems --DOD Instructions 3200.6 and 3200.9 have been issued. These and a lot of other letters and memos have been written and speeches made to present the new view and emphasize the need. The effort has centered on improving the management of development contracts. Pressure has been applied and will be applied until the fleet can live with the equipment.

These new ground rules for R&D management have been compared by Admiral Booth (4) to the negotiation of a contract between the CNO and the Chief of Naval Material.

> "The Chief of Naval Operations, as the customer, is demanding a materiel program which wisely invests the resource made available to the Navy."

One major facet of the new rules is the "economic sanctions" applied. Sound planning for development contracts, including the appropriate consideration of reliability and maintainability, is a prerequisite for the authorization of funding. To meet the new requirements will, for the Bureau, mean a new approach to contracting. But first we'll discuss the old words in their new meaning.

2. DEFINITIONS

2.1 RELIABILITY AND MAINTAINABILITY

The words Reliability and Maintainability will be used extensively, so I would like to start with an intuitive definition. Reliability is the performance characteristic of equipment that reflects its ability to operate satisfactorily long enough to complete its assigned mission. It is an index of the excellence of the design and of the operational integrity of a product. Higher reliability means fewer breakdowns - longer periods of trouble free operation. Maintainability is the performance characteristic that reflects rapidity, ease and economy of maintenance and repair. Higher maintainability means reduced requirements for skilled personnel, less down time for equipment.

The engineering approach to design concerns itself with specific functional performance. Will the equipment do what we want? Reliability Engineering asks "How long?" Design Engineering starts with the assumption the equipment will work. Reliability engineering starts with the assumption it will fail. Design for performance is concerned with how "effective" the system is in operation. Design for reliability is concerned with how long the system can function without failure.

2.2 DESIGN BASIS OF RELIABILITY

How are systems or equipments designed? There are actually very few new parts in any design. In developing a new equipment the designer selects parts (bearings, linkages, seals, power supplies, servos) that have been previously used, adapting them to his requirements. Each of these parts has some history of applications and some history of failures. Where failures occurred the design was changed until a satisfactory design was achieved. As a result of experiment, testing and trying new combinations, empirical rules for the use of the part have been developed. The designer of a new system uses these previously developed rules with established analytical techniques to produce a usually acceptable design.

In a new design, the designer must make a certain number of trade-offs or compromises. Usually several possible configurations are studied, the advantages and disadvantages weighed and one finally selected which, in the opinion of the designer, best meets his objectives. Within the specific performance requirements, two extremes of approach might be found. The conservative, or over-design approach, emphasizes high reliability. Excess weight or cost, even marginal performance, may be accepted to assure reliable performance. (An example might be the reduction in hydraulic working pressure on the periscope hoisting cylinders to prevent use of excess pressure on the seals). The optimistic, or performance oriented approach, emphasizes development of specific performance beyond the requirement, or low weight or cost (hoping the reliability will be adequate). This approach represents a bid for recognition, or the solution to a challenging problem.

Either approach can lead to serious modifications after the equipment is manufactured. The conservative approach may incur changes to "fix" overweight or poor performance problems. The optimistic approach may require changes to "fix" reliability problems.

But Admiral Schoech said in November,

> "We can no longer afford the 'build one and try it' approach with a subsequent 'get well' effort to patch on reliability, maintainability, etc."

The intermediate approach, considering all the requirements for reliability and performance in each decision is clearly better than either extreme. This approach requires some criteria, ground rules or method of analysis for making decisions. To establish such criteria or methods we look back to traditional design methods.

Designers design from experience. They use knowledge gained from their own and other people's experience to put together an equipment that will work. They are familiar with the relationship of cause and effect. In their experimentation and observing the results of other peoples efforts they have classified some configurations as "good" - they work, and others as "poor" - they don't. They have learned that properly conducted experiments are repeatable because of the cause-effect relationship.

The design for a specified reliability can take the same approach. Failures are repeatable. There is no such thing as a chance failure. Every failure that occurs is caused by the implacable operation of physical laws. Wear, overstress and progressive deterioration are physical events caused by physical conditions. A part used in a system is subjected to the operation of these laws in a reasonably consistent way. It may be expected to survive on the average a fairly predictable length of time.

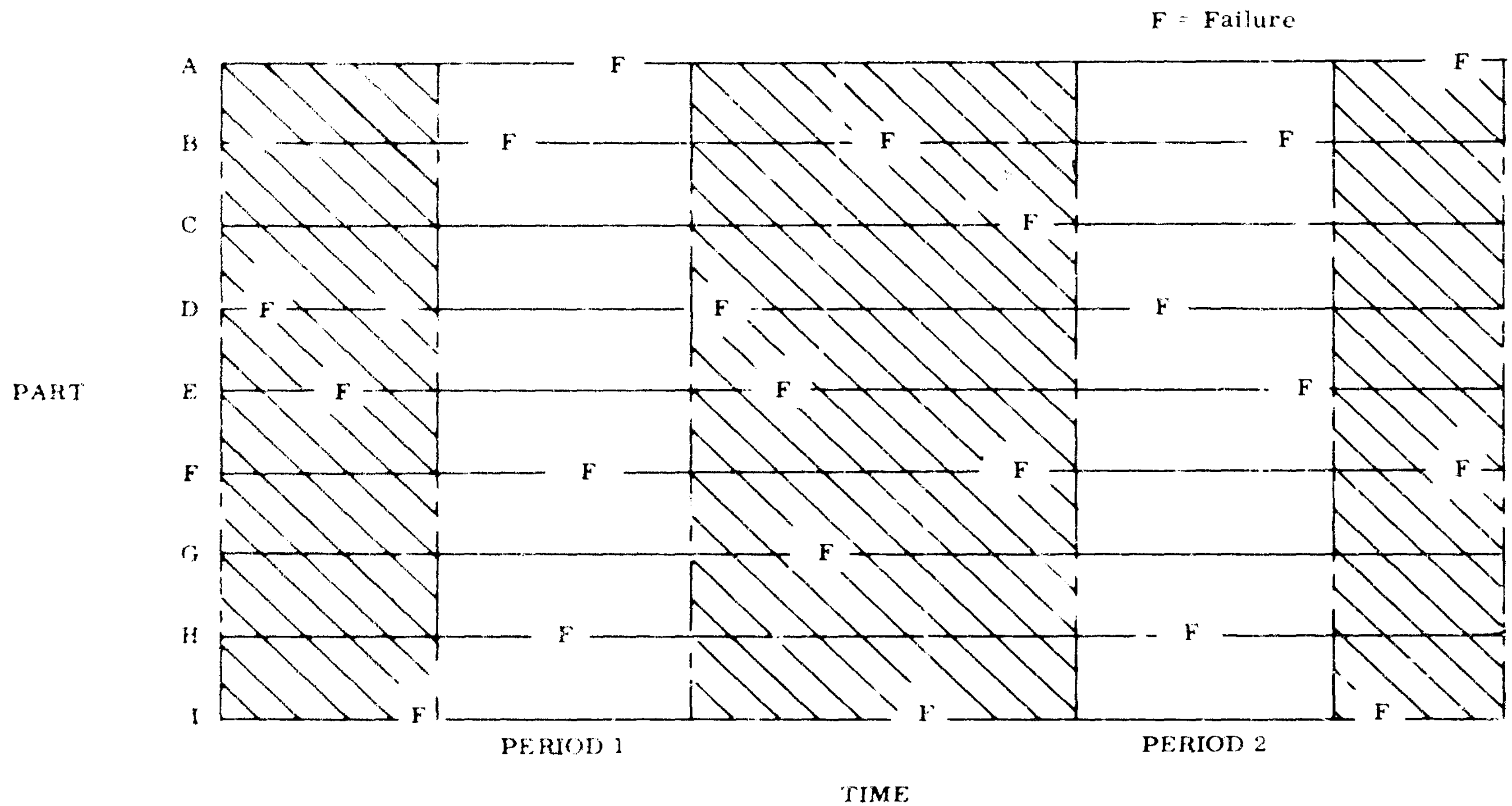
As parts were originally designed and developed, their reactions to certain combinations of pressures, dimensions, loadings, lubricants were evaluated. Certain combinations were found usually successful, other combinations were rejected. This was the source of the analytical design rules or criteria previously mentioned. But each analytical technique uses a go-no go, good-bad criteria. We can, and in a few instances have, determined, <u>how</u> good or <u>how</u> bad. The life expectancy for each part under a particular set of conditions, and how such life expectancy varies with changes in the conditions, can be established.

A system composed of these parts, each with its own characteristic life, exhibits a characteristic "random" failure pattern. Random, as used here, describes a situation where nearly the same number of failures occur in any two equal periods of time.

Figure 1-10 portrays a system of several parts, each failing (denoted by F) at its characteristic frequency. The system failure frequency is shown for two discrete equal periods of time.

We can thus establish a figure of merit, characteristic of the system, to evaluate reliability. One such figure of merit we call

RANDOM FAILURES



the Mean Time Between Failures (MTBF), computed by dividing the total operating time by the number of failures.

This figure of merit can be used to evaluate the design. It can be predicted in the design stage, before production of equipment starts. From the information obtained on prior test programs we can determine whether that system life will be satisfactory, as well as information on how to improve it by selection of working stress levels, tolerances or other factors having an effect on the life of the parts. This is a significant refinement to the "traditional" approach to design in that part life at the design conditions is predicted and compared against pre-assigned requirements, so that design conditions may be modified to improve the failure characteristics of the design before the equipment is built.

2.3 DESIGN BASIS OF MAINTAINABILITY

We have talked about failures as if this were the end of the line. It isn't so. Failures have to be repaired. They may be repaired immediately, to continue the operation. Or they may be repaired later when equipment and personnel are available. The oftener the equipment breaks down, the oftener it must be repaired. If an equipment has a MTBF of 100 hours, repairs are required about every four days. A large number of equipments, or equipments with a large number of parts (since failures usually occur to parts) can create a sizable repair workload. It can overtax our repair capacity and our budget.

The cost of repair or replacement of any particular part in a system can be estimated fairly closely. The prediction of MTBF, just discussed, will establish how many times per year, or how many times over the life of the equipment you would expect failures of that part. It is simply a matter of accounting to estimate the cost of repairs to the system for its lifetime.

Similarly, the length of time it takes to repair any particular part, assuming an appropriate number of workmen, can be estimated. From the predicted frequency of repair actions and the estimated time to accomplish each, a frequency distribution of times to repair, and hence a Mean Time to Restore (MTTR) can be computed. This MTTR is used as a figure of merit to describe the maintainability of the design.

The Mean Time to Restore is a designed-in characteristic of the equipment. To reduce the MTTR, the designer studies the actions necessary to accomplish the repair to each part, finding ways that the task can be expedited by changes in design. Typical examples are improved access (particularly emphasizing short life items), modular design or planned replacement at higher levels of assembly to reduce detail assembly and adjustment times.

As we have indicated, the reliability and maintainability achievable in a design are within the control of the designer. He can determine how much he needs. He can select alternate approaches, each of which meets his prime requirement. He can select the one which best meets his secondary objectives (low first cost, low maintenance cost, short down time). Having selected the approach, he can design the equipment so that the predicted failure rates of the parts will not cause the equipment to fail more frequently than permissible, or so that the estimated repair time remains within the permissible down time.

2.4 DEGRADATION OF RELIABILITY AND MAINTAINABILITY IN PRODUCTION AND USE

The designer establishes the maximum achievable reliability by his design. Poor manufacturing processes, poor inspection, inadequate maintenance or improper operation can reduce the observed reliability below that which is inherent in the design. The development of reliability in a design can be compared to a tree. The characteristics of the tree are established by the seed, but harsh environment can disfigure or dwarf it. The design is the "seed" of the equipment. The equipment can never be better than the design. But errors on the production line, or carelessness in maintenance can prevent the inherent reliability from being achieved. (Figure 1-13).

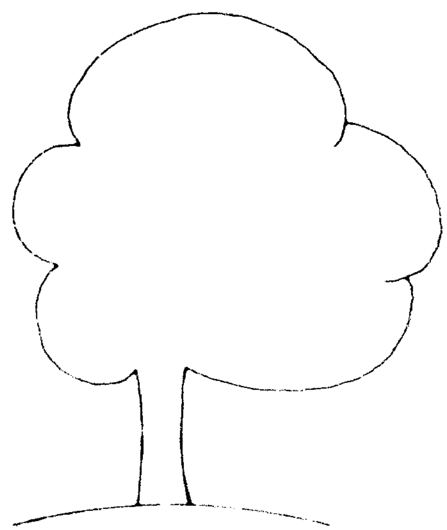
The approach to high reliability and good maintainability is sound engineering. The techniques and procedures we will demonstrate in this course are those techniques and procedures a "good" designer should use in designing. The various program aspects, design practices and procurement procedures that make possible the achievement of reliability in design and its retention in manufacture and use must be initiated, controlled, and audited by the engineer responsible for the procurement.

3. COVERAGE OF RELIABILITY & MAINTAINABILITY TRAINING COURSE

This course is designed to provide an initial exposure to the principles of design and procurement for high reliability and maintainability. In the short time planned, we can only expose the engineer to the principles and practices and put in his hand the techniques used. The gradual increase in capability to use the methods will require time, practice, and support from your

EFFECT OF HARSH ENVIRONMENT

A



B

reliability specialists.

We will be teaching powerful methods. We will provide enough understanding of the mechanics of the various operations to enable the engineers to estimate the cost that the use of the method entails and the return to expect. We will teach the philosophy that the decision the engineer makes should weigh the expected return against the expected cost, applying costly methods only where it is economically justifiable.

3.1 RESEARCH AND DEVELOPMENT PROGRAMS

In new designs, reliability is achieved through sound engineering during the design and development. The reliability techniques we will be teaching represent improved design practices, a sharpening of design disciplines, a deliberate orientation of the design to specific reliability requirements.

In the development of new systems, Mr. J. W. Roach, Assistant Director (Engineering and Management) ODDR&E, defines (5) the Reliability and Maintainability policies of the DOD as follows:

1. Reliability and Maintainability goals, stated in quantitative, mission-responsive terms must be established.

2. The Reliability and Maintainability goals shall be the basis of technically realistic requirements that can be contractually specified with appropriate demonstration plans.

3. Reliability and Maintainability can be obtained only by sound engineering during design and development.

4. As stated, Reliability and Maintainability must be designed into the equipment, but must be designed in on a system basis and must be subject to trade-off considerations with all other characteristics such as weight, size, cost, etc.

5. Reliability and Maintainability are the responsibilities of the project management organization.

6. Assurance of Reliability and Maintainability requirements achievements can be obtained only by constant monitoring by the project manager and his staff, utilizing carefully conceived plans for periodic review and for selected demonstrations.

In its life cycle, equipment passes three stages, development, production, and operation. DOD Instructions 3200.6 and 3200.9, as well as Mr. Roach's discussion of DOD policies, refer to the first stage, the initial development of new systems.

3.2 SHIPBUILDING PROGRAMS

In the Bureaus sphere of interest, new design occurs in many situations not funded as part of the Research and Development program. For each new ship class, a significant amount of re-design is performed. Even where no new design is planned, each procurement of a component or a system offers the opportunity to re-evaluate the reliability and maintainability and improve the design. If reliability improvement were religiously and consistently accomplished, the problems of the Fleet of the future would be significantly reduced.

3.3 FLEET IMPROVEMENT PROGRAMS

But the problem we described--the high cost of maintenance, the dissatisfaction of the operating forces--concerns equipment already designed and built, systems in the Fleet today. In this equipment, improvement is needed. The approach to improvement this equipment must be the same as that required for new devel... ment.

Improved reliability and improved maintainability can only be achieved by improving the design. Requirements must be establ... and the system redesigned and rebuilt as necessary to meet the requirements. One saving factor is that a large part of the un reliability will be found to be due to a small number of compon... An organized search for the bad actors with improvement in main tenance of operating records and reporting of failures and a systematic analysis of the total system each time a part of it ... selected for change, would result in an orderly, economical impr... ment

4. THE CNO-CNM DIALOGUE

Mr. Roach's first point in DOD policy on Reliability and Maint... ability was that goals, stated in quantitative, mission-respons... terms must be established. In a speech (4), R. Adm. C. T. Boot... stated,

> "When we state an operational requirement, we are generating a dialogue between the CNO and the Chiefs of Bureaus which ... the basis of our mutual understanding of the product we expe... and the cost and time schedule on which we expect it. It is ... the course of this dialogue that we must learn to inject quantitative reliability criteria."

It is in this dialogue that the Bureau must work with the operating forces to define reliability requirements, tempering the definition with the realities of achievable limits as well as cost and schedule. The definition should include:

(a) The level of essentiality (or importance) of the system.

(b) How the operating forces expect to use the system.

(c) How frequently and how long it could be down without materially affecting the mission or operation.

(d) What the relation of this system is to other installed systems.

(e) What kind of skills and what number of personnel with these skills could be made available to maintain and operate the equipment. What else the personnel are required to maintain or operate.

(f) When the equipment is needed in the Fleet. What event, situation, or other capability defines this time.

(g) What level of funding is planned or permissible to acquire and support the system.

It is important to note that the CNO cannot set realistic requirements by himself. High reliability is not necessarily the goal; but rather, the prime objective is to obtain systems that will operate satisfactorily and meet the mission needs at a reasonable cost and with reasonable time schedules. The dialogue is necessary to establish what these mission needs are and what can be provided within budget and time constraints.

5. BUREAU OF SHIPS IMPLEMENTATION

5.1 HOW RELIABILITY IS ACHIEVED

Having established the requirements, the next stage, implementation, is the Bureaus. Definition of requirements and their specification in numerical terms is not enough. As Mr. Roach pointed out, reliability must be designed into the system. It must be kept in through manufacturing, use, and maintenance. If it's not there in the basic design, it can't be put there except by fixing the design. And changing a design, and retrofitting the equipment, if far more expensive than doing the design right the first time -- before the equipment is produced.

The practical approach to achieving the required reliability is controlling the designer, requiring him to give adequate consideration to reliability and maintainability in the design. This is done by teaching the designer, and requiring him to use and document sound engineering disciplines, practices and analyses. Control of his activities is accomplished by formal documented audit of his considerations and decisions by well-qualified designers in his field -- usually senior designers in his own unit.

Quantitative requirements are necessary to describe the degree of reliability and maintainability desired. Demonstration is necessary to confirm that the requirements are met, but the verification must be supported by a good, solid assurance that the designer himself is considering reliability and maintainability in his design in an organized, understanding, and effective way. Later sessions will explain how this is done -- suffice it for the present to say this can be done, is being done in industry today.

5.2 MANAGEMENT'S TASK

As the top management of the Bureau of Ships, you can make it possible or impossible for your engineers to work toward improved reliability and maintainability. We won't eliminate your problems. Management's task is solving problems. In the solution to the problems discussed today we believe that the approach taken by management must include:

1. Understanding the relationship of sound engineering to true reliability and maintainability.

2. Understanding the relationship of reliability and maintainability to cost of acquisition and ownership.

3. Applying this understanding to the management of the Bureau's business in design, development, and procurement.

Paraphrasing a statement of Dr. Harold Brown (6), We have recently surveyed the reliability status of a number of system development programs in all three services. Our intention was to estimate how much management attention is being given to substantive reliability activities. One specific action that I feel needs to be taken without delay is to assure that those with line responsibility for development management at all levels have sufficient knowledge of reliabil[illegible] [illegible]iques and methodology to perform their management respons[illegible]ties in this area.

Let me elaborate a minute on the approach to developing management capability in improving Reliability and Maintainability.

First an understanding of the concepts taught. We expect to convince you that by the rigorous control of the contractors' reliability programs, reliability can be improved in the design and manufacture, that this new concept is not only practical and economical in the new development programs, but will also provide you with increased economy and less time and effort lost in the main part of your business. We expect to convince you that the approaches we teach are good engineering, with better definition of method of achieving that excellence of design we are looking for. We will demonstrate that the concepts are sound and the cost reasonable.

Second, the application of this understanding to the Bureaus business:

The concept of design for a specified reliability is not universally applied across the Bureau today although it is extensively used in electronic areas and R&D programs. Integration of reliability and maintainability requirements on a total ship basis is not apparent in shipbuilding, conversion or fleet improvement programs. With the recognition of the total system concept, we expect you to initiate the implementation of reliability improvement programs as a part of the Fleet Improvement Program.

The effectiveness of a reliability improvement program depends not only on the available control techniques and the competence of the personnel but also on management's active interest and understanding of the problems. The best way to motivate an engineer is to let him know that the top management will not tolerate anything less than his best efforts. To evaluate the efforts of the engineer requires that the top management read and understand the progress and problem reports. To pass the word back down requires that the top management react to the reports, even with as little as a hand-written comment or request for more information.

To instill in the engineers the concept that reliability and maintainability considerations apply universally, rather than only in R&D, one obvious step is to develop a reporting procedure that gives equal emphasis on reliability and maintainability whatever the program. The PERT and milestone concepts are familiar to the Bureau. Whichever concept is used, a standard requirement that each report include a section on reliability and maintainability goals, achievements and problems would initiate consideration of reliability by the engineers and provide management with visibility of the level of consideration.

The establishment of Shipbuilding and Operating Fleet reliability improvement programs require coordination across the Bureau and with the CNO. The initiation of a program to analyze the present situation and determine what the present problems are, to establish reliability and maintainability goals for each system in which such goals are applicable, and to establish reporting systems to provide management visibility of the progress toward achieving the goals, can only be initiated from the top management level.

5.3 SUMMARY

Why should you work toward improvement of reliability and maintainability? I can summarize in a few words:

1. It will improve the effectiveness of the Fleet.

2. It offers ultimate dollar savings in maintenance, repair, and logistics.

3. It can eliminate the need and reduce the cost and effort of "fix" programs.

4. It wisely invests the resources made available by the customer by matching equipment to resources.

5. It improves customer satisfaction.

6. But, most of all, good reliability and good maintainability are "good" design, achieved by the logical application of sound engineering analytical methods.

As top managers of the engineering effort, you have a heritage to be proud of, the outstanding capability and performance of the ships you designed and built in the past. As the technical corps of the Navy, it is up to you to assume the mantle of leadership to maintain in this complex technological era that traditional excellence of design to assure that the equipment furnished to the Fleet reflects "good" engineering and dependable performance.

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Chapter 2

REQUIREMENTS DEFINITION

Chapter 2

REQUIREMENTS DEFINITION

The development of reliability requirements requires an understanding of what reliability is and how it is achieved.

1. DEFINITIONS OF RELIABILITY AND MAINTAINABILITY

Reliability and maintainability are performance characteristics of systems. They express how well functional performance capability is kept available.

1.1 RELIABILITY

Reliability is defined as "the probability that systems or components will perform their intended function for a specified period under stated conditions." Probability means the fraction of attempted uses of the system that will be successful. A parameter of interest in the measure of reliability is the Mean Time Between Failures, defined as the average Stress Time between failures. Reliability is defined by three factors:

(a) The intended use or function required to be performed. From the intended use we derive a definition of failures, the incapability of performing the function.

(b) The specified period. From the intended use, we can determine how many periods or cycles of use will occur on the average for each expected failure. For an equipment with an MTBF of 240 hours, our reliability for a 24-hour period would be 90%. That is, about one day in ten we should not be surprised to have it down.

(c) The stated conditions. For any system, a severe environment will reduce the reliability, increase the average frequency of failures. Environment includes weather, imposed stresses such as temperature or vibration and the human "climate", skills of operators.

1.2 MAINTAINABILITY

Maintainability is defined as the speed or economy with which a system or component can be kept in, and/or restored to full performance capability.

A maintainability function is used to quantify maintainability. It is defined as "the probability that when maintenance action is initiated under stated conditions, a failed item will be restored to operable conditions within a total specified downtime." Again it is defined by three factors:

(a) Definitions of failure. This is the same as for reliability.

(b) The specified period of time. This is the time between occurrence of a failure and restoration to performance of the function that can be tolerated within the planned use of the equipment. For a system, the sum of all restoration times divided by the number of failures is called the Mean Time to Restore (MTTR).

(c) The stated conditions. Conditions under which a repair or restoration action occur include the numbers and skills of personnel, the restoration philosophy, logistic support (tools, equipment, parts), instructions, the working environment.

2. THE INTENDED USE

2.1 THE FUNCTION

The purpose of creating a system is to provide for the performance of a function, such as detection or tracking of targets, steering a ship, or whatever. The user is interested in the performance of that function at specified times based on the nature of his missions. The penalty for failure of the function can be assessed from the nature of the mission.

Development of a technical approach presupposes the recognition of a requirement and of a capability. The requirement must be evaluated in terms of the operational function. The capability is defined in terms of a technique or technology related to the operational function. This capability includes the ability to continue performing the function with failures at an acceptable rate and within the capabilities of the repair forces to maintain.

2.2 THE CAPABILITY

The technique or technology proposed will include the basic nature of the systems, radar, computers, or hydraulics. The function to be performed will indicate how the systems will be used, duty cycle, and probable environment. The penalties associated with equipment failure and failure to repair within a specified time can be predicted and values of reliability expected to be acceptable proposed. These values can be compared against the present capability of whatever industry is involved as shown by presently available similar systems and an estimate made of the amount of development effort which will be required to achieve the acceptable value.

2.3 THE REQUIREMENT

Every system developed must be responsive to a General Operating Requirement. The need for the system and the nature of its use must be stated in or inferred from such a requirement. A system to be used in a ship must be responsive to the functions imposed by the missions and tasks assigned to that ship.

In attempting to define a requirement for reliability, these questions must be asked and answered:

(a) What is meant by the failure of the system? The answer can be stated in simple terms: the failure to perform its function. This requires the statement of function in specific quantitative terms with specified tolerances. For example, a radio transmitter may send out a signal. If the signal is too weak the receiver will not receive it. This must be considered a system failure. So function cannot be defined as transmitting the signal but must include a range of power transmission as well. Carrier frequency, noise, directivity and other factors must be included in the definition. (See chapter 3).

(b) How frequently may failures be tolerated? The determination of this answer must be made by the intended user. Any reliability desired can be developed into a system, but any incremental increase must be developed at the expense of cost, time, weight or capacity. The trade-off must be made, starting from an original estimate of capability versus cost, by comparing the penalties associated with various levels of development of reliability until a satisfactory solution is found.

(c) What will be the environmental conditions surrounding the use and employment of the system? This question refers to natural and induced environments such as exposure to weather, high accelerations, sudden shocks. It also refers to the "human climate", skills of operators and maintenance personnel. It concerns the natural habitat of the system during its lifetime including periods of inactivity as well as activity. The environment will exert a large measure of control on the reliability achievable within present capabilities as well as cost of improvement.

(d) What is the planned cycle of operations? This question refers to the frequency as well as the duration of operations. It describes the functions to be performed on each type of mission, the length of time the functions are needed, covering each and every mode of operation of the system.

These questions are answered in the objective of the development. Let's look at the Research and Development Plan.

3. THE RESEARCH AND DEVELOPMENT PLAN

3.1 MISSION ORIENTATION

The Research and Development Program (3) (except for basic research) is oriented toward specific missions in particular environments. The basic input into the R&D program comes from the Navy and Joint Long Range Strategic Studies, which define the future roles and mission of the Navy. The long range threat, potential capabilities of possible enemies and the expected political climate are assessed. Where the long range studies assess the period beyond ten years, the Navy Mid-Range Study is concerned with the period out to ten years. The Joint Strategic Objectives Plan provide objectives for the 5-8 year period.

Upon issue of an edition of the Navy's proposed mid-range shipbuilding objectives, operational commands having cognizant interest submit recommendations on missions and tasks to the DCNO (Fleet Operations Readiness).

The statement of Mission and Tasks approved by the CNO for each type of U. S. Naval ship provides the key to a ship's ultimate capabilities, characteristics and cost. It furnishes a broad statement of the purpose for which the ship is to be designed and the tasks which the ship can be expected to accomplish.

The sponsor for the type ship in OPNAV amplifies the information contained in the statement of missions and tasks into a single page characteristics delineating the significant features and capabilities of the new ship which is furnished to the chairman of the Ships Characteristic Board. The type sponsor prepares formal R&D requirements to provide capabilities required but not yet developed. The 5-year Force Structure and Financial Program initiate the start of budgetary action for the acquisitions of the hardware.

The development and establishment of the Five Year Force Structure and Financial Program (FYFS&FP) have emphasized the necessity for defining the Navy's mid-range shipbuilding and conversion program with an accuracy and in detail comparable to the budget submission increment. The shipbuilding and conversion programs submitted to the Secretary of Defense for approval must therefore be justified by the Navy in terms of requirements, technological feasibility, production availability, characteristics and cost.

3.2 DEVELOPMENT OF SHIPS

The Ships Characteristic Board has one prime objective, (Figure 2-7), to insure through timely recommendations to the Chief of Naval Operations that the characteristics of all naval vessels not only meet, but anticipate wherever possible, the requirements of naval warfare incident to approved mission and tasks.

The specific tasks performed by the SCB are:

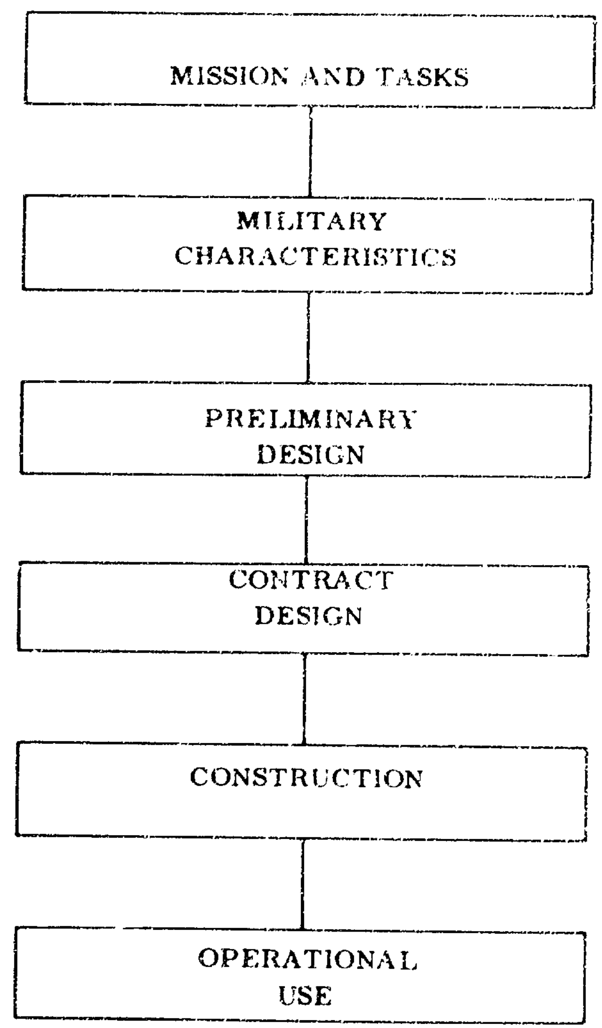
(a) With regard to all naval vessels:

(1) to recommend, based upon primary guidance from the Standing Committee, Shipbuilding and Conversion, the nature and extent of such installations as may be necessary to meet operational requirements after consideration of their effect upon other characteristics and when applicable the installation of items still in a research and development status, after consideration of their compatibility with research and development plans.

(2) To review the arrangement of material, instruments, and facilities to ensure efficiency in operational use.

(3) To make recommendation to CNO and the developmental agencies relative to the adequacy, weight and moment requirements, compatibility, etc., on all types of

LIFE HISTORY OF A SHIP



developments of shipboard equipment, particularly electronic equipment, in order that new equipment shall be adaptable to shipboard utilization in fulfilling operational requirements.

(b) With regard to new construction, conversion, and modernization of ships, landing and service craft, and consideration of merchant type ships planned for Naval acquisition:

(1) To study the requirements and guidance furnished and from such study develop the broad ship characteristics which will support the mission and tasks assigned.

(2) On the basis of estimates furnished by the Material Bureaus in connection with design studies, to advise the Deputy Chief of Naval Operations (FO&R) and the Chairman, Standing Committee on Shipbuilding and Conversion, of the probable costs of the ships in the program.

(3) To recommend the characteristics in such detail as necessary to guide the bureaus in their preparation of plans and specifications.

(4) To review pre-characteristics design studies before the annual program is developed by the Standing Committee on Shipbuilding and Conversion, and before detailed plans and specifications are finalized by BuShips, and recommend changes when required.

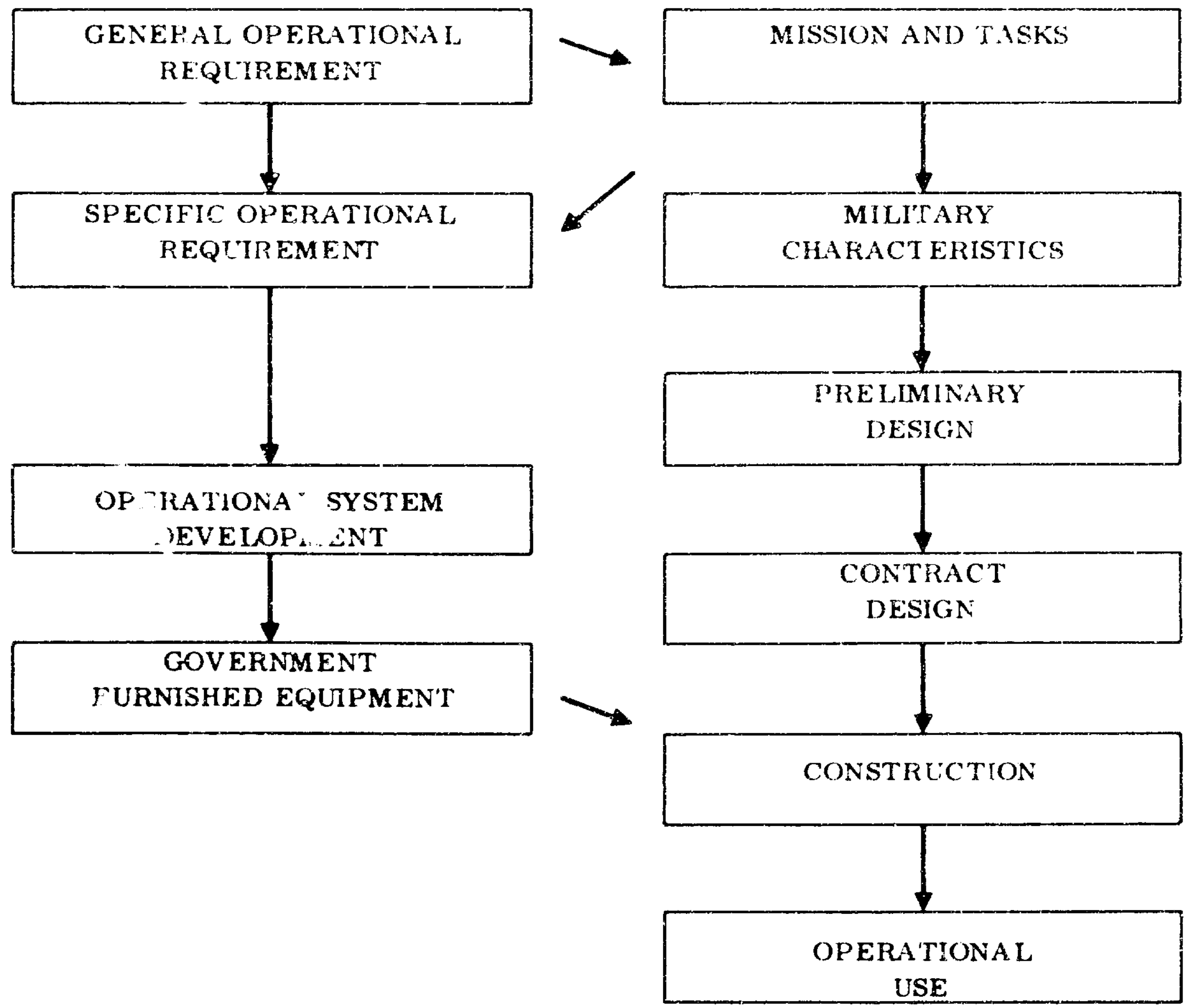
The characteristics of the ship are generally defined in terms of speed, cruising radius, type of propulsion, size, weapons, and other special equipment to support the missions and tasks. In the effort to anticipate the needs of the Fleet and to match or anticipate potential enemy capabilities, the early introduction of newly developed capabilities into the fleet is mandatory.

These new capabilities are being developed today (Figure 2-9) and are planned for future development in the Naval Material Research Objectives. Each system or capability in a ship had at one time a development phase. (Figure 2-10).

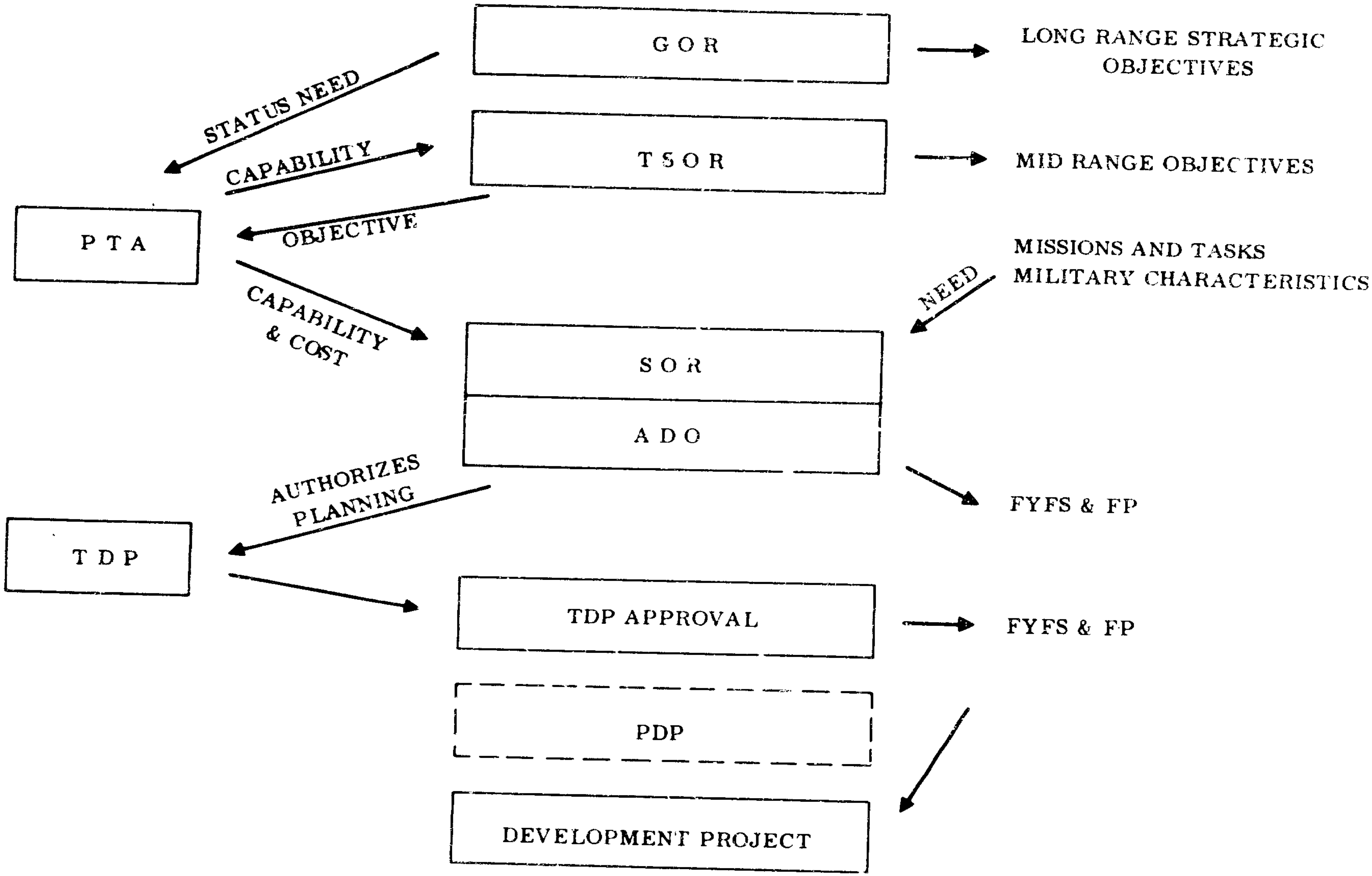
3.3 DEVELOPMENT OF SYSTEMS

Several years ago it was realized that significant improvements

DEVELOPMENT OF AN OPERATIONAL SYSTEM



DEVELOPMENT PHASE



were required in R&D management to avoid the large cost overruns, schedule slippages and performance/design changes that had become a pattern in major development projects. During these past several years, in order to effect significant improvements the DOD has tried a number of relatively new things (not necessarily new in concept but in emphasis) among which are Incentive Contracting, Contractor Performance Evaluation, Cost-Effectiveness Analysis, Categorization of R&D and Project Definition Phase. The most important objective of the PDP is to provide an adequate basis to assure that management decisions to proceed with, cancel or change development projects are made on a total system and total cost basis which includes realistic cost and schedule estimates for the production phase.

The other objectives are to:

(a) Establish firm and realistic specifications.

(b) Define precisely interfaces and responsibilities.

(c) Identify high risk areas.

(d) Validate technical approaches.

(e) Establish firm and realistic schedules and cost estimates for the production phase.

(f) Establish schedules and cost estimates for planning purposes for the total project (including production, operation and maintenance).

PDP can be considered to be one step in a series of steps in the research to production sequence. It is that step which immediately precedes the full scale development and is the means of defining it. The steps prior to PDP are necessary to assure that the proposed development project is ready for PDP. These include technology and building block component developments which are accomplished without specific reference to the proposed system development program, and studies specifically aimed at the proposed development, such as trade-off studies, feasibility studies, cost-effectiveness, operations research, etc. The development and studies prior to PDP must assure that the prerequisites to PDP have been met:

On January 18, 1963, Dr. Brown sent a memorandum to the Departmental Assistant Secretaries (R&D) covering several major concepts in the management of research and engineering. One section of this memorandum treated Project Definition and set forth positive ground rules for its application to new projects. These ground rules required that PDP be used for all new Engineering Development and Operational System Development projects with cumulative RDT&E funds of $25 million or more, and provided for application of PDP to other projects at the direction of DDR&E or the option of the department. DOD Directive 3200.9 which was just issued, includes these same ground rules for application with one addition: that Engineering Development or Operational System Development projects with anticipated expenditures for production investment of $100 million or more are also required to use a PDP.

The terms Engineering Development and Operational System Development and their place in the R&D structure are outlined in DOD Instruction 3200.6. The Engineering Development and Operational System Development categories are the last development categories in the research to production sequence and are developments intended for Service use. Inadequate or tardy definition of these projects results in drastic consequences in terms of total costs (including R&D, production, operation and maintenance), schedules and operational effectiveness.

The Project Definition Phase (Phase I) is a formal step preceding full scale development (Phase II) during which preliminary engineering, and contract and management planning are accomplished in an environment that encourages realism and objectivity.

While the project definition phase requirement applies to new projects of $25,000,000 or more, the basic concepts of management of a development are applicable across the board. Where the basic concepts were not followed in the original development of equipments in use in the fleet today, we still have the design and SOFIX problems. And they won't go away. As each problem is identified, the fire drill starts again.

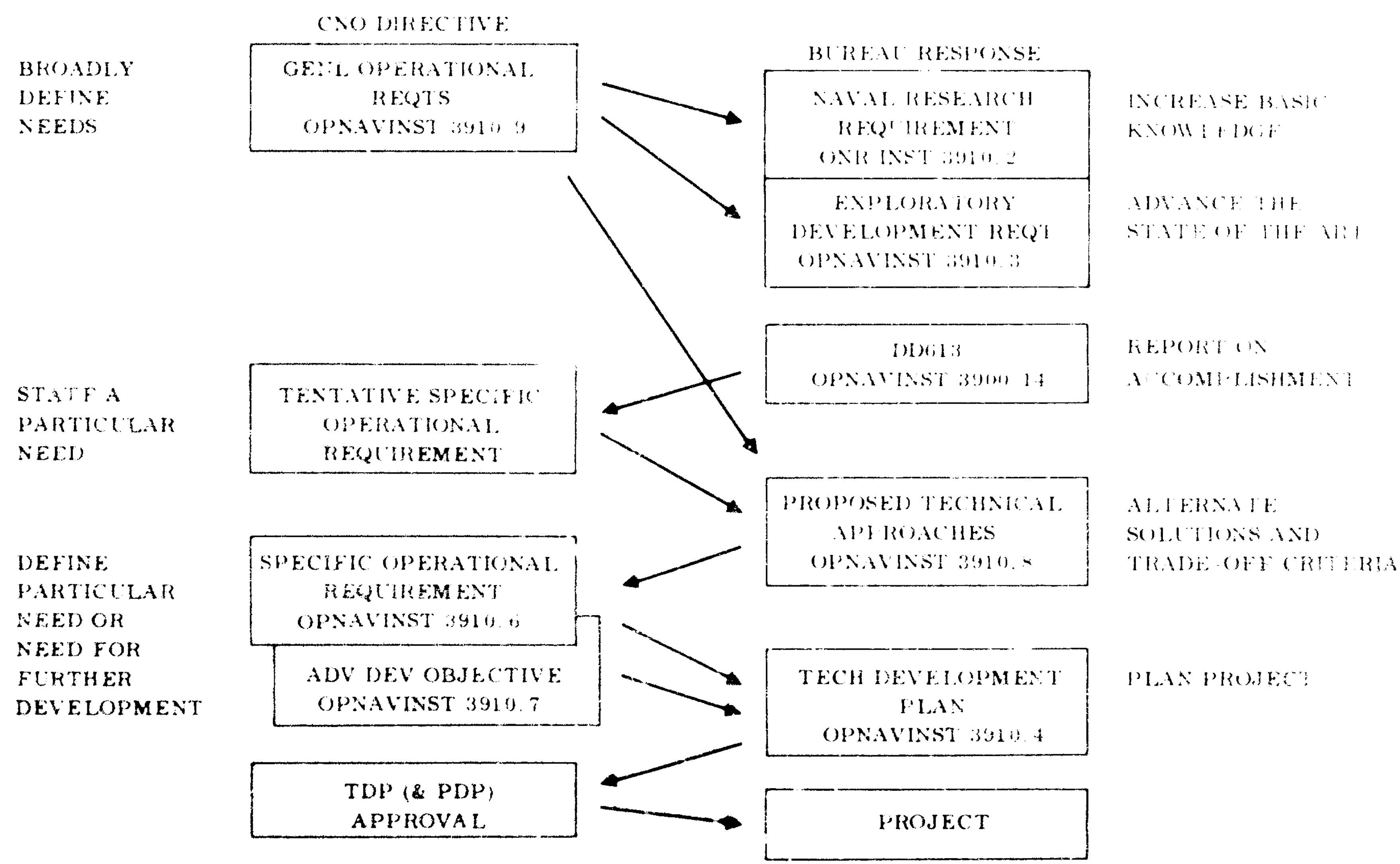
3.4 NEW DEVELOPMENT: A MANAGEMENT PROBLEM

The problems to which DOD Instructions 3200.6 and 3200.9 are addressed are not technological problems, but problems of management. Let's look at the structure of the dialogue between the CNO and the NMSE (Figure 2-13).

The various documents covering the definition of requirements are:

(a) General Operational Requirement (GOR). A GOR is a generalized statement of needed operational capability prepared by the CNO.

DOCUMENTATION OF REQUIREMENTS



(b) Tentative Specific Operational Requirement (TSOR). The TSOR is a document originated by the CNO by which the CNO requests certain information of a technical nature which is necessary in order to determine if a valid Navy research and development requirement exists.

(c) Proposed Technical Approaches (PTA): The PTA are documents prepared by the NMSE for the CNO outlining technical approaches by which a particular capability may be achieved.

(d) Specific Operational Requirement (SOR): The SOR is a document by which the CNO states the need for the development of a particular operational capability.

(e) Advanced Development Objective (ADO). An ADO is a document prepared by the CNO and addressed to the CNM which states a need to conduct certain experimental studies, tests and development effort for the purpose of establishing the potential capabilities of a new weapon concept, the technological feasibility of developing a new system, and to develop greater accuracy in the cost, time, and performance estimates required to establish financial acceptability of a new system.

(f) Technical Development Plan (TDP). A TDP is a plan developed under the direction of the NMSE for the purpose of documenting those actions, procedures and resources which are required in order to achieve the capability described in the SOR, or those actions required to achieve the objectives outlined in an ADO.

3.4.1 Evaluation and Review of the RDT&E Program As the development of weapon systems becomes increasingly more costly in critical resources, it is mandatory that existing development programs be continuously appraised and reviewed in order to permit timely reallocation of resources or program curtailment whenever such action appears to be required. In order to provide for this appraisal, standardized reporting procedures have been established. The following paragraphs describe several of these management-oriented reports.

(a) Project Report. DD Form 613 contains the basic program information required by management for the analysis and review of RDT&E projects in the DOD Research and Exploratory Development categories.

(b) Monthly Project Evaluation (MPE). The MPE is a monthly report submitted to the CNO by the bureau or office having management responsibility for a project in advanced development, engineering development, or operational systems development. The purpose of the MPE is to direct the attention of the top Navy RDT&E management echelon to present or potential problem areas in the RDT&E program.

(c) Research and Exploratory Development Program Highlights. This report is to keep RDT&E administrators and managers informed as to progress, or lack thereof, towards objectives within the categories of Research and Exploratory Developments. These highlights include all significant accomplishments and problems, actual or anticipated, within the approved programs for Research and Exploratory Development. Program highlights are reported on an exception basis.

(d) Hotline Report. This report provides a formal method of ensuring that the ASN(R&D) and DCNO(D) are made quickly aware of RDT&E problems which are, or have the potential for, seriously affecting RDT&E projects. This report will provide interim coverage when major or critical problems or other significant events occur or are anticipated between regular monthly progress reports.

(e) Quarterly Project Reliability Summary. This report serves as

(1) A reliability annex to the TDP summary by providing the minimum acceptable reliability requirements and the contract goals as the basis of the reliability rating (in the Monthly Project Evaluation) of each project in engineering development and operational systems development, and

(2) A convenient quarterly progress report to top Navy Research and Development management in these two categories of systems development.

3.5 IMPACT OF PROPOSED TECHNICAL APPROACHES

The Chief of Naval Operations has been charged with the responsibility of developing the maximum capabilities in the fleet consistent with the strategic objectives and the Five-Year Force Structure and Financial Plan. In the evaluation of needs to support Missions and Task against Capabilities, Schedules and

Costs, the Proposed Technical Approaches constitute the Bureau's bid on the job offered by a GOR or TSOR. The CNO, in his management, must try to spend his money in the way most likely to achieve the most pressing of his needs. The PTA must sell the Bureau's understanding of the need and appreciation of the soundness of the approach. Failure to convince the CNO that the equipment can be provided, within the required time, within budget limitations and with adequate capability, may cause him to decide that the risk is too great to pursue the project. An SOR might never be issued.

4. CONTENT OF A PROPOSED TECHNICAL APPROACH

Reference (6) requires that the PTA contain, in addition to the functional and operational description of the system and the problem to be solved, an estimate of the operational effectiveness of the proposed system. This shall be stated in terms of performance reliability, operability and maintainability. Alternatives in performance, cost and development time are required to bracket the proposal in performance and duration of the development schedule.

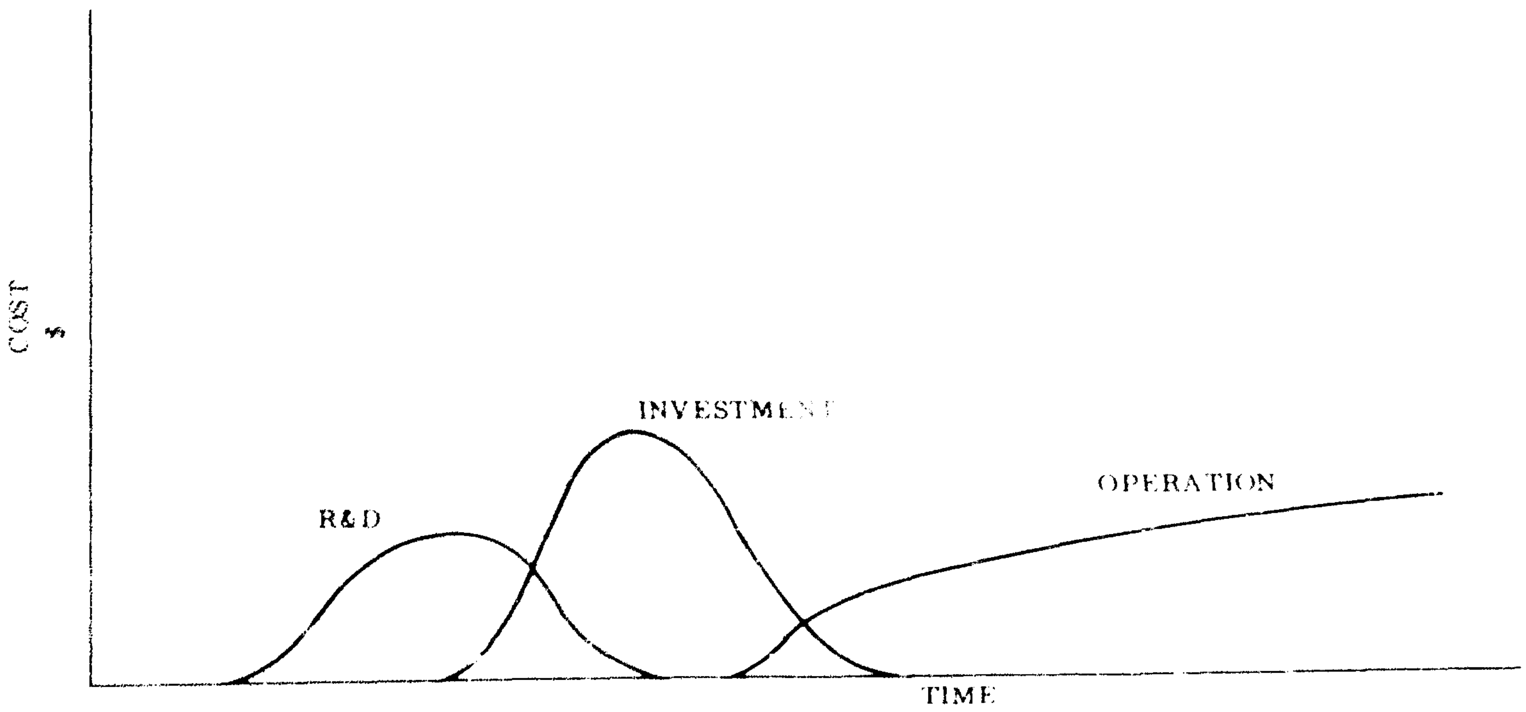
4.1 RELIABILITY AND MAINTAINABILITY

4.1.1 The development of the reliability expected from each of the alternatives should consider the present state of capability of the particular industry as well as the anticipated difficulty in improvement. The cost and time to develop the equipment with present state of the art reliability and the cost and time expected to develop the maximum feasible reliability within the schedule constraints should both be shown. Both values should be compared to the assumed acceptable value.

4.1.2 Similarly the development of present industry capability and maximum maintainability development within the schedule constraints should be evaluated and shown in the alternatives in the PTA.

4.1.3 The cost consequences for each level of reliability and maintainability should be estimated using the planned operational duty cycles previously discussed and estimated number of failures and consequent cost of repairs as well as anticipated cost of maintenance and operation (Figure 2-17). The impact on personnel numbers required and training requirements should be estimated.

COST OF ACQUISITION AND OWNERSHIP



4.2 DEVELOPMENT OF RELIABILITY REQUIREMENTS

An example of the development of reliability and maintainability requirements is provided.

4.2.1 We consider a requirement for a shipboard fire control system. The function is to actively defend the ship against enemy aircraft. Since the system is quite complex, we break it down into its subsystems. The four subsystems are:

(a) Detection system: to detect aircraft approaching the ship.

(b) Tracking system: to provide continuously the slant range and bearing of the designated targets.

(c) The fire control director: consisting of director radar, computer and controls.

(d) The weapon: a surface to air missile.

The weapon and director system are already developed and available. The system to be developed is the detection and tracking system. Acquisition range required is 40 to 50 miles based on assumed aircraft speed, time required to develop tracking information and reaction time for target acquisition and time of flight of missile. The approach selected is a single radar with search and tracking capabilities with a computer to convert range and bearing to predicted position.

From comparison of data on operational systems very similar to the proposed new designs we can establish estimates for certain parameters of the new systems. These are considered the parameters achievable with present design methods. Performance is defined as the probability that the system, when operating within specification will accomplish its function. For example, performance for the search radar is the fraction of the time that approaching aircraft will be detected before they reach the minimum acceptable acquisition range of 40 miles. For the tracking mode it is the fraction of detected aircraft successfully identified to the fire control director.

	Search Mode	Tracking Mode
Performance	.95	.99
Reliability (MTBF)	118 hrs.	58 hrs.
Maintainability (MTTR)	3 hours	4.2 hrs.

4.2.2 The duty cycle or plan of operational use for the radar will be tested against three standards:

(a) A four-hour period (nominal) comparable to the normal duration of general quarters.

(b) A 90-day period comparable to a normal patrol or cruise.

(c) A four-year period, comparable to the expected duty tour between shipyard overhauls.

For the search mode the periods of interest are the four-hour and 90-day cycles. The radar will be operated continuously in the search mode, to detect the start of the attack. When the attack has started the tracking computer is activated to provide tracking on designated targets. The period of interest in the tracking mode is the probable maximum duration of an attack.

We can make the following assumptions:

(a) The equipment will be operated daily at morning general quarters and whenever an unidentified target is detected.

(b) About six of the operations will result in attack by enemy aircraft.

(c) The period of each operation, scheduled or unscheduled, will be four hours.

(d) Failures can occur only during operating periods.

The probability that the radar is operable in the search mode at any time a target might come within range is its availability,

$$A = \frac{MTBF}{MTBF + MTTR}$$

assuming that the radar set is designed for negligible preventive maintenance downtime during the 90-day cycle. Using the parameters previously determined, the expected availability in the search mode is .975. The probability that any target appearing will be detected in time is the product of probabilities for performance and availability. This product is .925. The reliability of the radar, operating in the tracking mode for the four hours, is .933.

The probability that the radar will perform its function of detecting the start of an attack and tracking aircraft for the four hours is the product of these, or .865. Assuming, as we did that six such attacks would occur in a 90-day patrol, the probability of successfully operating during six attacks would be .42. The risk (under the assumption of six attacks) of 3 chances in 5 of not surviving a 90-day patrol does not appear acceptable.

4.2.3 Alternate approaches: Improving the reliability of the search and tracking radars by a factor of four would improve the MTBF in the tracking mode to 232 hours giving a four-hour reliability of .983. This amount of improvement is considered within present industry capability.

The availability of the search radar in search mode is improved to .994. The improved effectiveness of the radar becomes .927. For a 90-day cruise with six actual attacks, the probability of successful detection and tracking is improved to .63.

With a performance improvement in detection of aircraft at 40-50 miles, the effectiveness will see a significant improvement. A performance improvement to .98, for example, would improve the single attack effectiveness to .957 and the cruise effectiveness (six attacks) to .77.

4.3 TRADE-OFF ANALYSIS

A trade-off analysis, showing these factors, similar to Figure 2-21 should be prepared to provide clear visibility to the CNO of the cost, schedule and performance factors to enable him to make a decision, based on a solid foundation, as to which course to pursue. Development of such trade-offs is covered in chapters 23 and 26. With this minimum level of detail, an SOR can be definitive not only of the performance characteristics but also of the level of effort to apply in the improvement of reliability and maintainability.

5. TECHNICAL DEVELOPMENT PLAN

Once the foundation is laid for the development program through a choice of objectives and the Specific Operational Requirement issued, the development of the plan for achieving the objectives is fairly straight forward. With the requirements and industry capability known, the plan for dependability requires a level of control adequately identified by the gap between present capabilities and requirements. The planning for accomplishment, however,

TRADEOFF WORKSHEET

	REQUIRED	APPROACH A	APPROACH B	APPROACH C
PERFORMANCE CHARACTERISTICS				
ACQUISITION RANGE	50 mi	50 mi	50 mi	65 mi
TRACKING	40-10 mi	40-10 mi	40-10 mi	50-10 mi
TRANSFER TO DIRECTOR		MANUAL	MANUAL	AUTOMATIC
SEARCH EFFECTIVENESS				
PERFORMANCE		.95	.95	.98
RELIABILITY		MTBF 118 HRS	MTBF 472 HRS	MTBF 420 HRS
MAINTAINABILITY		MTTR 3 HRS	MTTR 3 HRS	MTTR 3.7 HRS
TRACKING EFFECTIVENESS				
PERFORMANCE		.99	.99	.999
RELIABILITY		MTBF 58 HRS	MTBF 232 HRS	MTBF 186 HRS
MAINTAINABILITY				
OVERALL EFFECTIVENESS	.90	.865	.927	.957
DELIVERY SCHEDULE				
OPTEVFOR EVALUATION	JUNE 1967	JUNE 1966	JUNE 1967	DEC. 1968
PRODUCTION UNITS (2b)	DEC. 1968	JUNE 1967	DEC. 1968	JUNE 1970
COST				
DEVELOPMENT		5,000,000	6,500,000	3,200,000
PRODUCTION (20 UNITS)		60,000,000	65,000,000	78,000,000
OPERATIONAL (5 YEARS)		24,000,000*	7,000,000*	3,000,000*
REMARKS		PRESENT STATE OF THE ART	IMPROVED VERSION OF PRESENT EQPT.	DEVELOP AUTOMATIC TRACKING COMPUTER

*Excludes salaries of military personnel is the CNOs opportunity to judge the management effectiveness of the Bureau on the project. Lack of confidence in the outcome, based on inadequacy of planning, may still prevent initiation of the project. Inadequacy of the planning presentation in the TDP might well convince the CNO that the risks involved are too great for the gamble. The TDP must reassure the CNO that the Bureau is aware of the problems and is planning to overcome them. If this conviction is not clear, some other allocation of the funds may well be made.

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Chapter 3

SYSTEM DEFINITION

Chapter 3

SYSTEM DEFINITION

A system is a collection of components that are made to operate together as a unit. The term was originally used in the communication field to describe the various techniques (telephone, telegraph, wireless, amplitude modulation, frequency modulation, pulse modulation, etc.) used to transmit information from one location to another.

The term weapon system has been used for a collection of smaller systems. For example, the weapon system used for intercepting bombers includes the interceptor, airborne fire control system, armament system and propulsion system and in addition a ground-to-air communication link and possibly an automatic landing system. The interceptor is only a part of a still larger system called the Air Defense System which includes the early warning systems, anti-aircraft weapon systems, interceptors and associated GCI (ground controlled interception) systems and also the communication links which tie all these together.

A ship is a weapon system in the sense that it is a collection of systems which transports itself plus a load along some sea path to a particular destination with a specific purpose or function. The load, for military applications, consists of weapons and the destination is some operating area.

In the development of a highly complex system such as a ship, there is a major need to consider the interrelationships between systems. Unless such interfaces are considered, there is a great danger that efforts to achieve perfection in one area may reduce the overall effectiveness of the ship, rather than enhance it. It is often difficult because of the broad technical knowledge required to know how to make compromises judiciously. It will be the purpose of this chapter to describe some of the considerations that are involved in the development of integrated systems.

1. DEVELOPMENT OF SYSTEM APPROACH

1.1 DEFINITION OF SYSTEM TASK

As we discussed in chapter 2, the selection of the task for the ship is complex. Each ship has a variety of capabilities, one or more defined as primary, others as secondary. The primary capabilities are based on requirements for the class of ship as defined by the Ships Characteristic Board. Sometimes, as in the FBM, the primary characteristic is related to the weapon. Again, as in the DER it is related to detection and tracking equipment. Or, as in the MSO it may be related to counter measures equipment. The start of the analysis may then be the identification of systems that are used to effect the primary function or mission of the type of ship. The task of the ship is to support these primary systems.

1.2 SELECTION OF COMPONENTS

Having identified the primary systems of the ship, the next phase is the determination of the systems needed to support them. For a particular case these supporting systems may include Navigation, Propulsion, Ship Control, Electric Power, External Communications, Internal Communications, Search, Detection, Life Support, Damage Control.

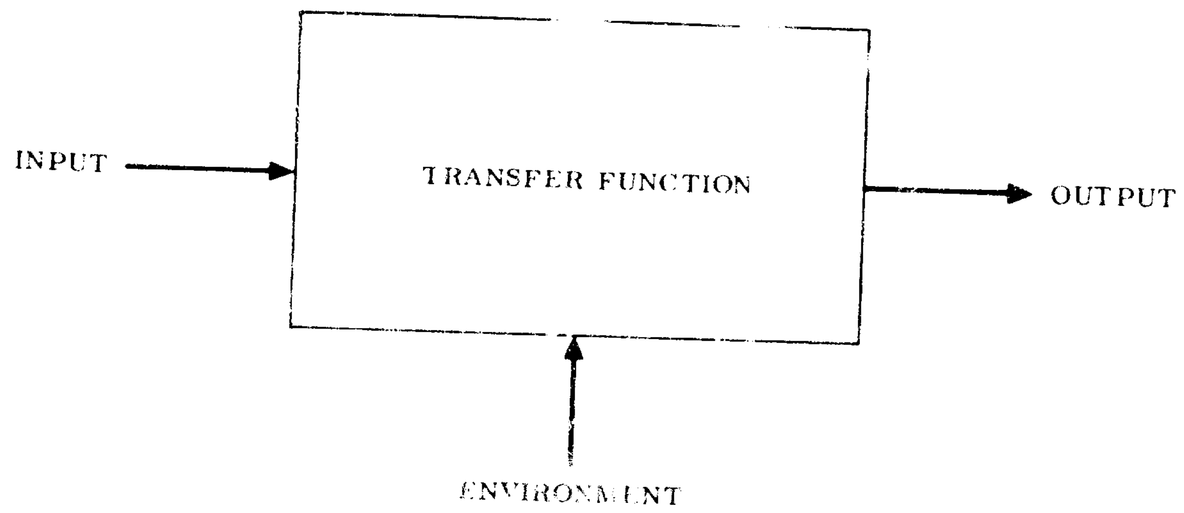
1.3 SYSTEM OPTIMIZATION

Having selected the primary and supporting systems an analysis must be made of the performance of this group to determine the characteristics which will result in an integrated system.

A useful aid to thinking at this stage of development is the system block diagram. A block diagram is a schematic description of the way the system operates. Each system or subsystem may be thought of as a box. (Figure 3-4). Certain inputs, such as signals, power, and decisions are required to make it perform its function. As a result of the inputs, the box produces a certain output such as position, energy, or other signals. The relationships of the output to the input is established by whatever mechanism is within the box. The effect of operation of such a mechanism we call a transfer function. The box operates under the influences of its environment which may have an effect on the transfer function to modify the output. A simple example might be a steam generator. On the provision of fuel and air (properly combined and ignited, of course) and water, the steam generator produces a flow of steam. The flow is controlled by variation in demand and the quantity of fuel and air burned. The transfer function includes the transfer of heat energy to the water.

A system consists of a number of such boxes. To describe the functioning of the ship, the systems are arranged in blocks with connecting lines to illustrate the flow of information. A typical block diagram for a generalized weapon system is illus-

SIMPLE MODEL



trated in Figure 3-6.

There are secondary relationships involved in these systems. Navigation may support the weapon directly. Communications provides the input to ship control. Electric power supports each other systems and is itself supported by elements of the propulsion system.

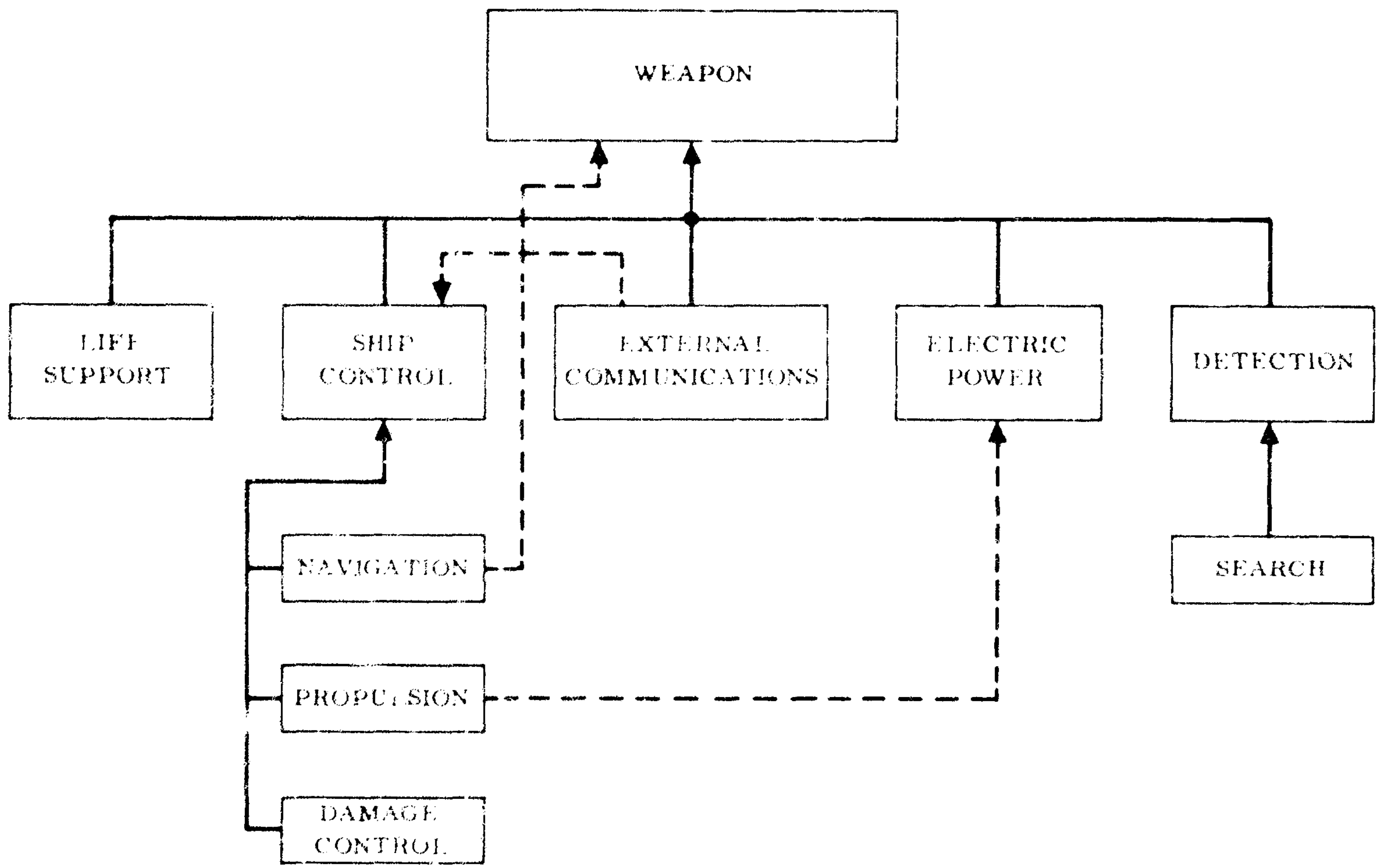
A complete diagram (usually much more detailed than that illustrated in Figure 3-6) showing all of the relationships is sometimes called the interaction diagram. The functioning of each system is described by the transfer functions which relate the outputs of each of the blocks in the diagram to its various inputs.

In the conceptual phase of design, these systems are not yet identified as specific pieces of hardware. Their inclusion as systems only identifies that "hardware" systems are needed to perform the functions. These functions need to be described to a greater level of detail, breaking the functions into subfunctions and these lower into sub-subfunctions until a conceptual equipment or assemblage can be named that can perform the function. For example, Navigation might include identification of position on the sea and identification of true North. It might also require information on the speed of the ship through the water. Several equipments can be named capable of performing these subfunctions. For position on the sea, Celestial navigation, LORAN or SINS might be considered, for identification of direction a gyrocompass, for speed a pitometer log.

The output of each such proposed system operating within its intended environment must be tested against the input requirements for all related systems. The trade-off is made; selecting the optimum systems capable of meeting all requirements from considerations of cost, schedule and performance parameters. The performance parameters should at this time include weight, space, speed, accuracy, reliability, maintainability, availability, etc. One very good way to accomplish this is to select, first, the key properties of the systems, such as response time, voltage, pressure, etc., which approximately describe the operation of the system. These are compared and values of the key properties selected which produce the best performance of the system task, accounting for the performance parameters named above.

Variations in the performance parameters are then tested against cost and schedule, keeping the key properties within permissible

TYPICAL BLOCK DIAGRAM



limits to arrive at an optimized system.

1.4 SUBSYSTEM DEFINITION

Having identified system function to general types of hardware capable of performing the functions, the next step is to evaluate the type of hardware to define the characteristics of the systems to be used. Working within the constraints already selected, the input and output for each system, the function assigned that system is again broken down, one level at a time until the subfunctions derived are each identifiable to an equipment. For example, "external communication for the command net," may be broken down into transmit and receive, requiring a transmitter and a receiver. Transmitting equipment may be available that meets the key properties and required performance characteristics already selected. If not, one can be synthesized by breaking down the function to the next level (Transmit to generate a carrier, modulate, amplify, and radiate). Working within the constraints imposed by the key properties, the components capable of performing these functions are tested against the performance parameters. The new performance parameters are then tested at the next higher level of functional breakdown to determine their effect on the optimization of the system. This successive breakdown to finer levels continues until each system is defined in terms of components accepted as within the state of the art.

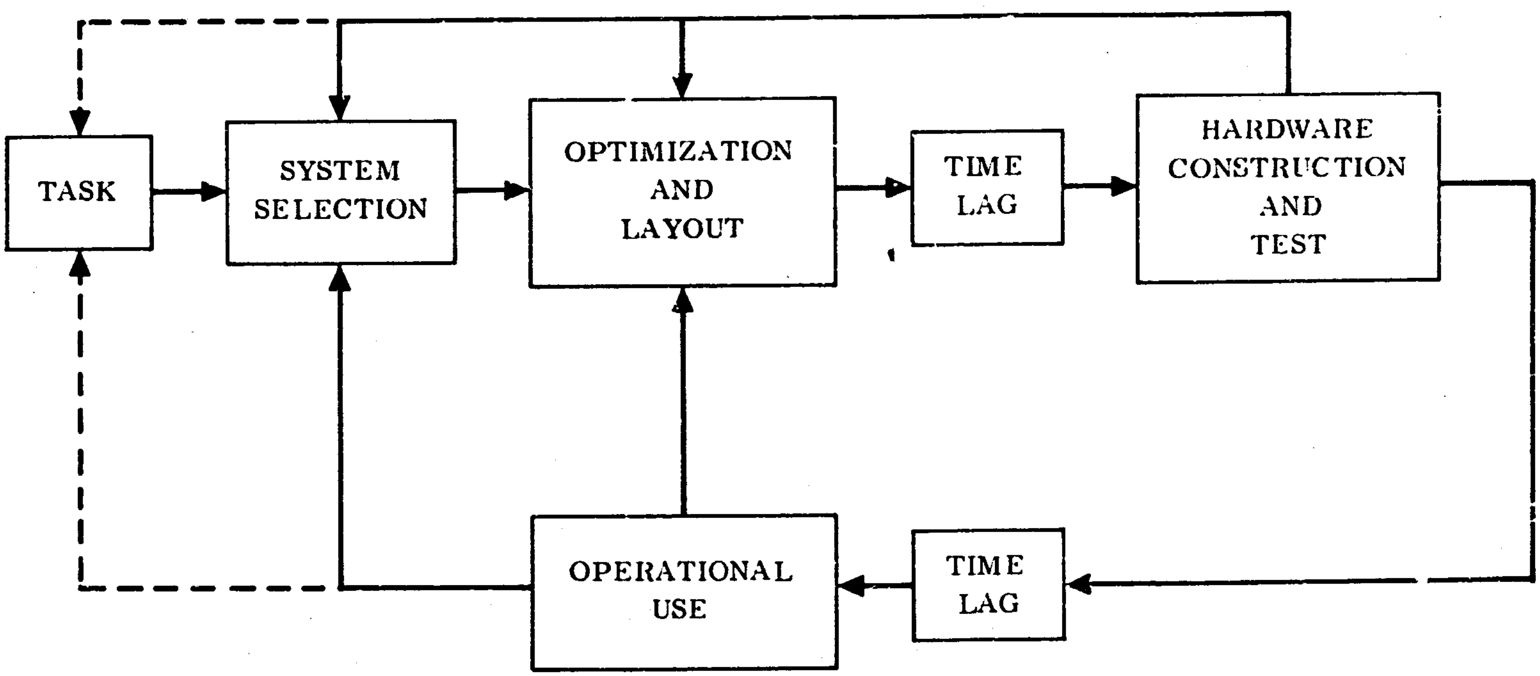
Using the developed values of the key properties, tentative specifications are made and designs and drawings are made and new estimates of the performance parameters are made. These new estimates, plus additional parameters, are fed back into the analysis while hardware construction is proceeding. Tests on the development hardware are made and these results are fed back into the analysis. A flow chart illustrating the entire operation appears in Figure 3-8. The information may flow continuously but the configuration can only proceed in steps for compatibility reasons.

The important concept here is the system Approach. The relationships between systems is continuously used as a control on the definition of the system. The approach insures compatibility and enables system optimization.

2. REPRESENTATION OF SYSTEMS BY MODELS

The system block diagram provides the basic skeleton for the system model. A model is an analytical representation of the

FEEDBACK IN ITERATIVE DESIGN



system in terms permitting assessment of the characteristic of interest. It describes what the system is; what, how and when it does it; and what external influences affect it. It contains descriptive data regarding the system permitting evaluation of the characteristic of interest when performance data is applied.

2.1 MODELS AND THEIR PURPOSE

The system model is the means by which relevant information is utilized in an organized manner to formulate estimates concerning the system. The model makes it possible to evaluate system performance with regard to a characteristic prior to actual production of the system. Perhaps more importantly, the model approach provides the means of evaluating the effects of design and development decisions on the system. This provides a sound, rational basis for design trade-off studies, design selection and parts selection. Finally, by means of a model, critical portions of a system in development or in use are identified. From this knowledge the needs for further development may be defined.

A model always expresses quantitative output (such as system reliability) as a function of component inputs (such as failure rates); accounting for all relationships between components (configuration).

An important application of the model is in total system trade-offs to obtain an optimum balance, within the mission and performance envelopes, between total cost, schedule and operational effectiveness of the system as discussed in Chapter 26.

Models such as these permit the design engineer to simulate alternative approaches, such as configurations or redundancy, to determine the probable effect upon Effectiveness and Cost. This provides a much sounder basis for trade-off than does intuition.

It is obvious that a model can be made extremely complex and detailed. In a detailed form it contains functional, analytical and logic block diagrams, environmental profiles, mission profiles, a list of ground rules and assumptions and a complete set of equations. But the model need not be extremely complex. A simpler model, consisting of a simple diagram and a few equations is adequate for many purposes. The model is a tool of design and should be no more complex than necessary to serve the immediate purpose. More, it should be kept flexible so that as additional knowledge becomes available, it can be added to the basic skeleton, with no reconstruction except as required to incorporate changes.

For major system trade-off studies prior to design or for pre-design apportionment the model will treat the system at the major functional block level as was done in Figure 3-6. General assumptions providing great simplification should be used at this point. Such assumptions are just as valid as those requiring elegant mathematical treatment, because of the lack of detailed knowledge of the system. All that is required at this point is a first approximation of functional block values. These will suffice for making the major trade-off decisions to establish the optimum feasible set of system requirements and to establish general design and development approaches.

As design progresses and more detailed knowledge of the system is made available, the model will evolve in detail and refinement. For prediction and especially for demonstration the model should reach the degree of refinement permitted by program and data constraints. Such a model will provide a basis for selection of design and parts.

The importance of a model lies not in the absolute values of numerics that it generates, but rather in the discipline of analysis and comparative analysis that it provides. The model is a frame of reference within which certain quantities are measured. These measurements will provide fair or poor approximations to the true values, depending on the completeness of the model and the quantity and quality of data supplied.

But the measurements have a great deal of relative accuracy. This permits comparisons to be made for the purposes of measuring progress and growth and of making trade-off decisions. Because a system model is necessary to arrive at major trade-off decisions and to establish system requirements, development and use of the model makes it possible to measure progress in achievement of these requirements. This process requires apportioning the requirements at the proper level of details and retaining the same general ground rules contained in the original statement of requirements. At the detail level problems are detectable by comparing measurements with requirements. Effects of corrective action can be evaluated. Although the true value of some characteristics or parameters may never be accurately known, the model allows useful measurements of these by comparison.

It is, therefore, not all-important that a specified requirement be accurate in an absolute sense, but rather that it be stated in terms that its achievement is measurable within program constraints.

2.2 SYSTEM MODEL ELEMENTS

2.2.1 Mission Objectives and Requirements: A system comes into being as a result of some operational requirement. A function has to be performed, and a system is designed and produced to perform the function. The system model begins with a mission objective, that is, a statement of the operational requirement. This requirement might be detecting and tracking a target, propelling a ship or any other objective.

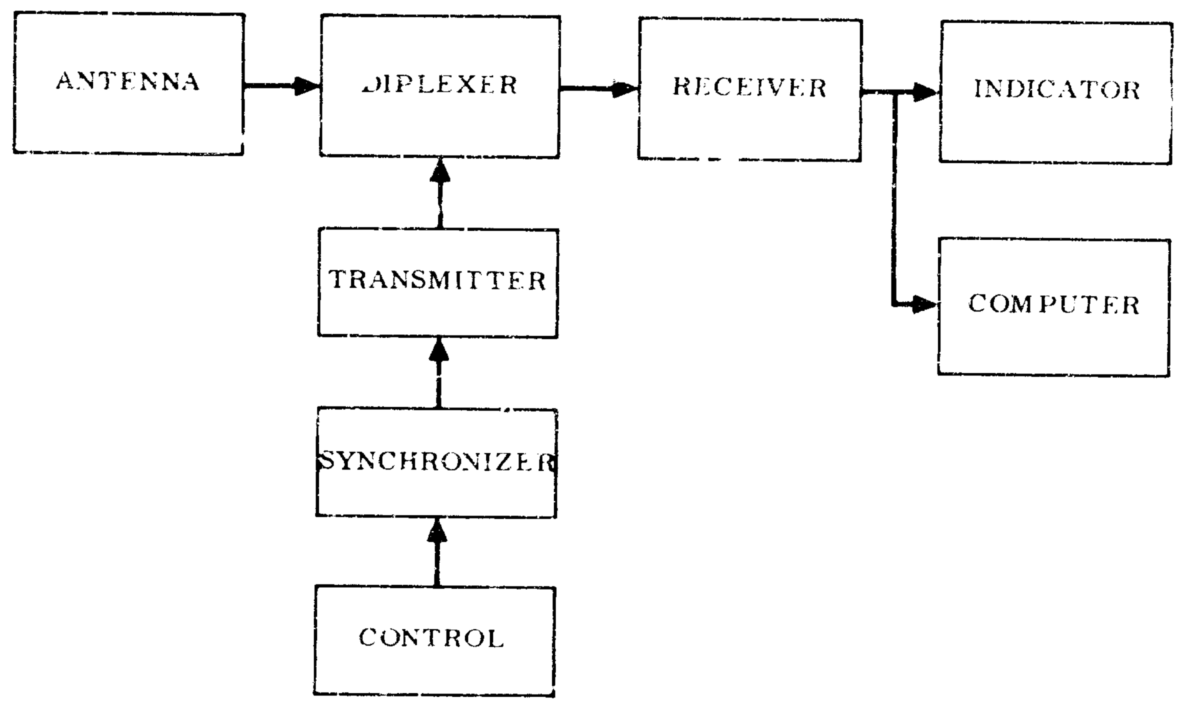
In order to meet these objectives certain functions must be performed. To detect and track a target a radar system might be selected. If a radar system is to be used for this purpose the subfunctions might include control, generation of an electrical pulse, radiation of the wave, receiving the return wave, separating the incoming wave from the transmitted wave, synchronizing a display with the outgoing pulse, abstracting information to provide input to the tracking computer and displays. Equipment can in general be named to perform each of these functions. (Figure 3-12).

Therefore, each function in the system is identified with a class of hardware to the extent required to estimate the magnitude of the development effort. In a propulsion system for example there is a fuel supply, burners, air supply, boilers (including preheaters, superheaters, etc.) steam lines, turbines, condensers, feed subsystem, reduction gears, screws and shafts. Each of these can be identified in some manner with one of the functions required for propulsion. A state-of-art constraint has now been imposed, in that general design approaches are now defined. No particular boiler has been specified, but the system will have at least one boiler, which, together with the accessories, will perform the function of energy conversion.

2.2.2 Event Sequencing and Operating Times: Now that system functions are identified and schematically related, a sequence or set of sequences of activities necessary to complete the mission objectives must be defined.

Along with the sequence of activities, the necessary system operating times are determined. This enables a time line analysis of the mission to be made. Mission activities are appropriately spaced on the time line to determine the operating state or mode of the system at any given time. From the system time analysis the periods of operation for each functional block is determined. The periods of operation (duty cycle) for each functional block are represented by time lines plotted on a scale

SYSTEM FUNCTIONAL BLOCK DIAGRAM



of mission time with activities shown. Some of the mission activities may occur at random times. This will be quite common for shipboard situations. It would be impossible to formulate an exact schedule of events for many shipboard systems. This should not present much difficulty. A sequence is necessary only to provide duty cycle times for equipment as a reference for requirements analysis. A typical duty cycle should be assumed and used for the analysis.

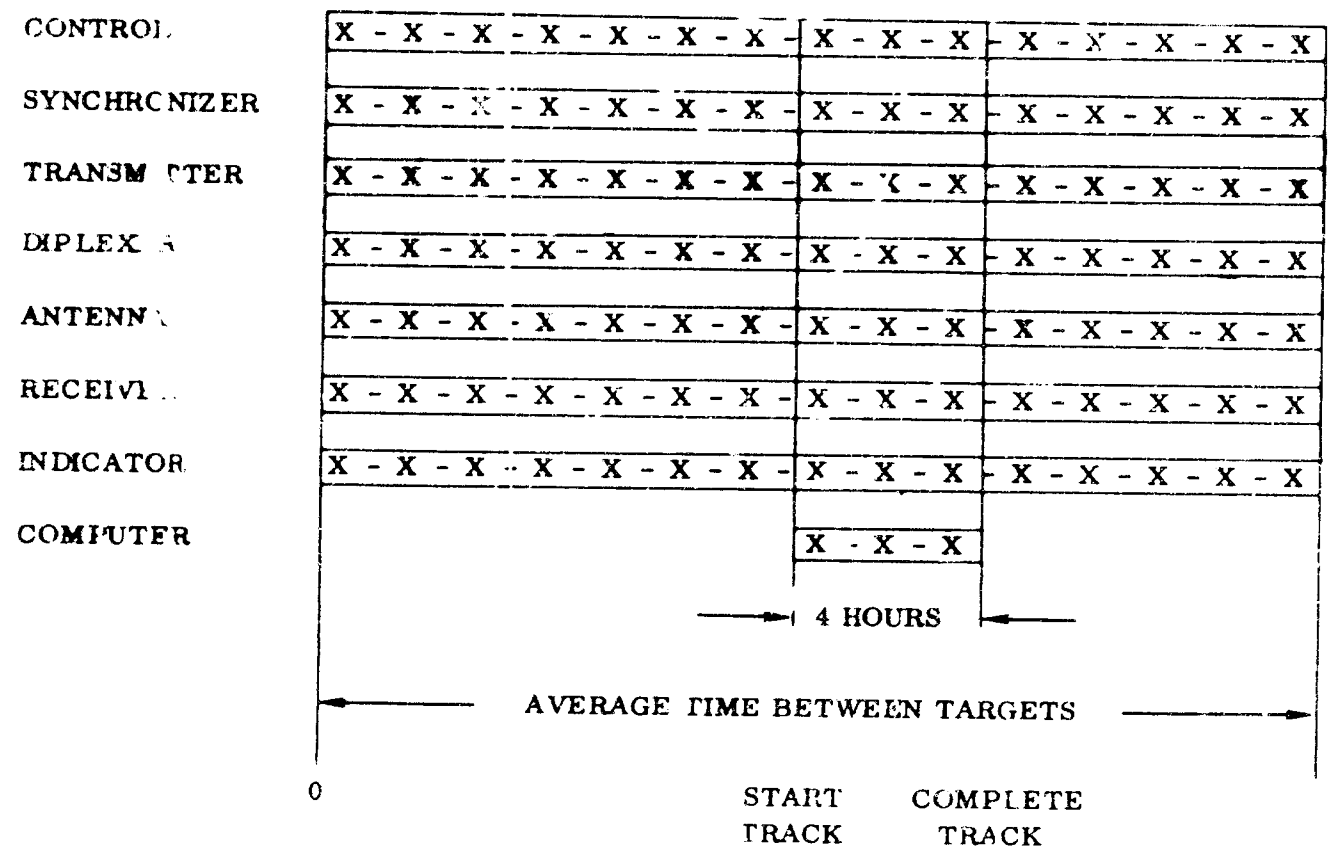
2.2.3 System Operation: The time line analysis already performed provides the basis for the study of system operation. The activities may affect operating modes in a manner prescribed by the function affected.

The radar system has a specified mission of 90 days of surveillance with a four-hour tracking period upon target acquisition. (Figure 3-14). Detection of a target is a random event, so that frequency of tracking periods is indeterminate. This makes no difference because all system elements operate the same during surveillance or tracking.

For the moment let us assume that the computer in our radar system is kept off during surveillance mode. Then, when a target is acquired the computer is switched on. It is kept on until completion of tracking, after which it is switched off for system return to surveillance mode. The time line for the computer would show this intermittent operation as a blank during surveillance and a line for the length of the tracking operation (four hours).

2.2.4 Environmental Profile: A description of all critical environments as functions of time for a system mission is called an environmental profile. On board ship it is not always feasible to consider environmental levels as a function of time unless the environment is the predictable result of a pattern of equipment operation. Many changes in natural or operational environments, such as temperature, ship motion, etc., occur randomly. Frequently the most practical way to consider environmental levels on board ship for estimation of reliability is to assume them to be constant. The system will, of course, be designed to withstand the most damaging operational levels. But for reliability analysis, the assumed environmental level should be an average value, somewhere between most benign and most severe, according to the anticipated frequency distribution of levels. The assumption of a single value represents a simplification in the model affecting the accuracy of the estimated absolute reliability. However,

RADAR TIME LINE ANALYSIS



assumption of properly chosen constant environmental levels makes the model sufficiently useful.

One example of a system whose environment is a function of time is an underwater television system. As the system is lowered in the water, the ambient pressure increases at a rate proportional to the rate of descent. The portion of the environmental profile describing pressure would indicate pressure increase to a maximum, a constant for some required time at maximum depth and decrease as the system is raised, all as a function of time. It is necessary to recognize the fact that this variation in pressures will be present. But for the purposes of reliability estimation, unless the failure pattern for the system can be determined as a function of varying pressure, a constant pressure will be assumed. This will probably be chosen as an average maximum level. The environmental profile will be used in this case as a check to assure that the problem of varying pressures has been taken care of by design.

The environmental profile for the radar system might look something like the following:

Electrical Subsystem:	Range	Nominal
Temperature	60^{o} to 95^{o}F	80^{o}F
Relative Humidity	20% to 80%	60%
Salt Atmosphere, concentration, etc.		
Antenna Subsystem:		
Temperature	-20^{o} to 120^{o}F	10^{o}F

It is necessary to state the ranges of values so that design can be checked at significant points within the ranges. Nominal values are chosen for use in making reliability estimates, as previously discussed.

2.2.5 Success/Failure Criteria: As discussed earlier, a system has one or more objectives to fulfill. In order to fulfill its objectives it is necessary that the set of measurable system outputs conform to a respective set of tolerances. These tolerance bands need not be equal to the designed tolerance ranges but should certainly include them. The ranges of required output values may shift as a result of a change of mode of system operation, as implied in the discussion of system operation. The same is true of input values as well.

If a system whose inputs and environments are within ranges specified for successful system operation performs an entire mission with its outputs remaining within tolerances required for successful performance, a success is scored. If the inputs and environments are within specified ranges and any system out= put deviates from its acceptable range at any time during the mission, it is considered a failure. If the system is restored to operation within a specified allowable repair time a mission success may still be achieved. Otherwise it will be scored a failure. If any input deviates from its specified range the result should be scored "no trial", unless it is conclusively shown that the apparent success or failure would have resulted without the input deviation. It is evident that in treating reliability data it is just as important to consider input con- ditions and environments. These system inputs affect system performance as much as do the outputs. An obvious case is a deck winch attempting to hoist too large a load. On the other hand, a PPI scope may be presenting an acceptable display, as measured in millilumens, only because the ship's a-c voltage is too high. Such occurrences often result in false reporting or non-reporting of failures.

The probability that the system will be able to meet the success criteria depends on how stringent the criteria are. The criteria are established from the system objectives and are the limits of acceptable ranges of operation as previous described. In order to obtain uniform reliability estimates, these criteria must be stated. They are also required in order to collect reliability attribute (success/Failure) data or interpret variables (output values) data.

For the radar system under study, the success criteria might proceed as shown below in incomplete form:

<u>Output Pulse:</u>

Power	8 magawatts min.
Frequency	2198 $\pm$ 5 mc

Pulse Width - etc.

Input sensitivity at 2198 $\pm$ 5 mc: 20 mv max.

Tracking Accuracy:

Range	±0.5
Bearing	±5°
Course - etc.	

These criteria are not necessarily equal to performance specifications but the specified tolerance ranges must be included within the success criteria. If the product meets all of the complete set of success criteria, this is no absolute guarantee that the system can detect and track targets 100% of the time that the system is so operating. A small target in rough seas may not be successfully tracked, or a target might not be detected in heavy fog. This is no reflection on the reliability of the system. It simply is not designed to cope with these situations. In other words, the input conditions in these cases of apparent system failure are not as specified. Therefore, though the system fails to meet its objective, it does not fail in its performance. Success or failure depends both on input and output performance.

3. LOGIC BLOCK REPRESENTATION

Up until this point the model elements discussed are those required for making any kind of rational system analysis. These elements are mission objectives, functional flow diagrams, time analyses, description of system operation, environmental profile and success/failure criteria. Some degree of information is required for each of these elements. The accuracy of the analysis depends on the accuracy and completeness of the input data for each element. How these data are integrated in the model will be shown.

3.1 SIMPLIFICATIONS

In the discussion of the generalized model, it was shown that the exercise of a model requires detailed data regarding the equipments, environment and interrelationships. All quantities in the model are time dependent distributions. Due to model complexity and lack of accurate data, it was further shown that such a model is difficult to handle in most cases. Simplifying assumptions which degrade model accuracy were given. Some of these are restated here:

(a) Drift failures may be neglected;

(b) System elements are considered to fail independently;

(c) A failure of any system element is considered to result in inevitable system failure, unless an alternate element or procedure can supply the failed function.

These assumptions make it possible to construct a logic diagram of a system from the functional block diagram. The logic diagram describes the system operation in simple terms, allowing immediate derivation of a system reliability equation. Several forms of logic diagrams are available, including one that utilizes symbols of gate functions and time delays. One, that is fairly easy to set up and understand, shows all possible alternate ways that the system can perform its function. This is illustrated in Figure 3-19.

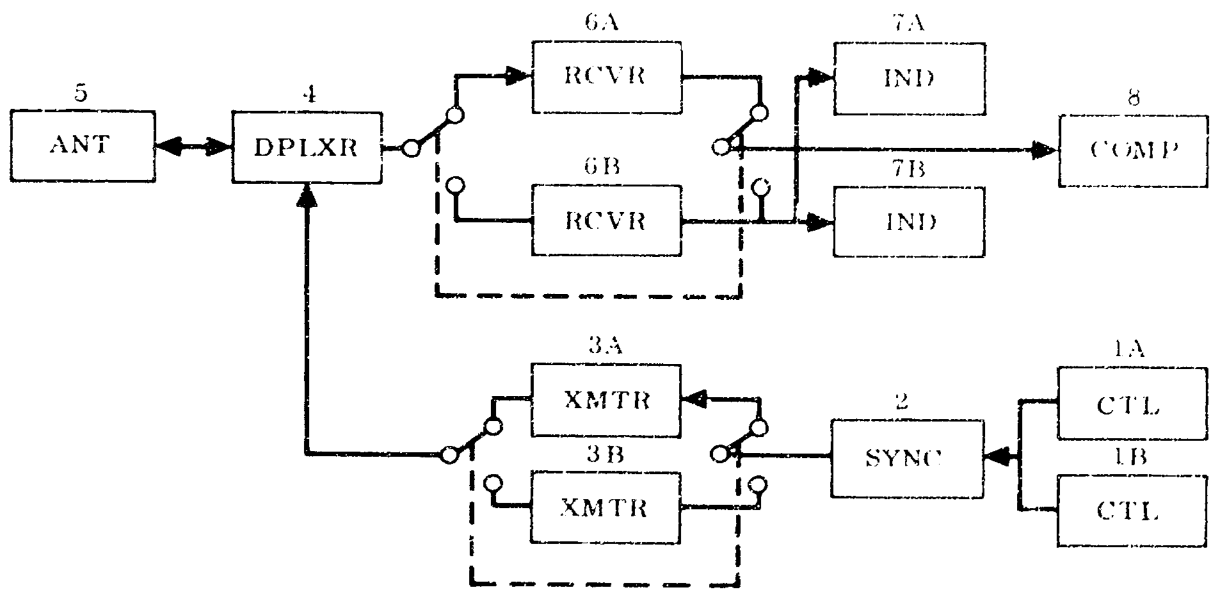
3.2 APPLICATION TO RELIABILITY

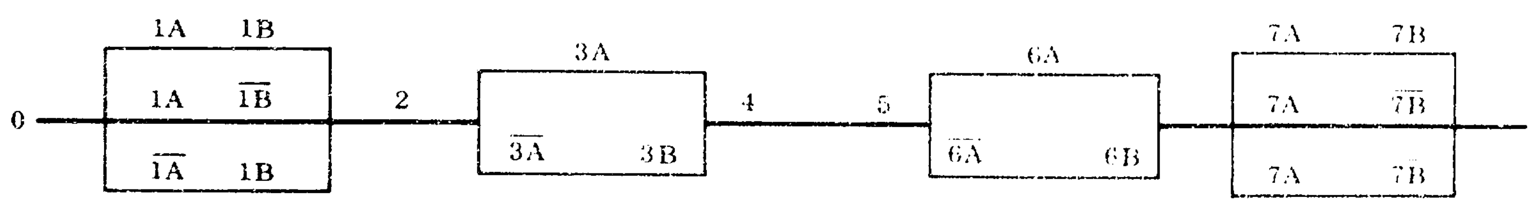
Estimation of reliability requires the use of a model to describe the system in terms such that application of available reliability data produces the required reliability evaluation. The model should be only as complex as the system and its requirements demand. It will range from a single function block with a single equation to a set of complex detailed logic diagrams with an elaborate computer program. Very complex models are seldom required for shipboard systems.

To provide useful reliability measurement, the model must be applied consistently. An assumption used for apportionment must also apply to prediction, demonstration analysis and support analysis. During design and development it is frequently necessary to alter initial assumptions as more knowledge of the system is gained. The consistency requirement of the model means that the latest changed body of assumptions be applied to analyses previously performed, if the results of these analyses are to be applied in the future. The purpose of consistency is to permit valid comparisons to be made. The measured achievement must be in the same terms as the requirement. Measured growth must be consistent with the period to which the growth is referred. The value of the quantitative approach to reliability is realized only when these measurements are made within the same frame of reference. It is this consistency that provides discipline in reliability.

The reliability analysis model can be expanded to include other characteristics or program constraints for trade-off analysis as discussed in Chapter 25 and 26. The trade-off analyses provide an insight into the contractor's understanding of the development

RADAR LOGIC DIAGRAMS





and its problems. In the proposal the bidder should set forth a conceptual reliability model sufficent to indicate approaches to anticipated development problems. The usual trade-offs involve reliability and maintainability within the constraints imposed by development budget and schedule, production costs and field support of the system. A thorough understanding of the constraints and their effects is required for valid trade off. The amount of effort for trade-off is determined by the level of reliability required and the severity of the constraints relative to complexity of development.

4. APPLICATION OF THE MODEL TO DECISION MAKING

As the design gets underway, the Criteria and Configuration permit selection of an appropriate model technique from the available tools. The model is constructed by the design engineer, or by reliability engineers if so delegated. As tentative design environmental and sequence information is developed, and best available data (such as failure rates) is plugged into the model, it can then begin to provide useful output.

Although an apportionment of reliability and other design assurance elements may have been made, the first model prediction is a far sounder apportionment. Any discrepancy between predicted and required values can be apportioned rationally on the model structure. If rational apportionment to lower levels will not reach achievable values, the design engineer has a problem.

From this time on, the model is used for regular (such as bi-weekly) predictions of reliability and other design assurance parameters. Updated plots of the prediction vs. schedule provide Engineering supervision with regular progress reports. At the overall system levels, these provide progress reports to Management.

Since the model always expresses outputs as a function of constituent inputs, derivatives thereof may also be published. A Sensitivity List may show the ratio of output improvement to an arbitrary improvement of each component input (such as halving the failure rate), in rank order of potential improvement. Thus the design engineer can quickly spot the best opportunities for improvement.

Another derivative is the Criticality List, which ranks components in the order of probability of causing system failure, taking failure modes and effects into account. This provides a basis for design review, critical component identification and action, and special handling.

As design problems are brought into focus, by the model or otherwise, the model can be used to evaluate alternative solutions. The design engineer merely substitutes alternative configurations and/or components into the model, and lets it calculate the consequences. This is especially powerful if the model accounts for total cost, as it provides the economic basis for a change.

The system model approach is a methodology designed to give cohesiveness and visibility of the problem. It is one of many methods of organizing data to identify the complexities of interrelationships between the equipments. In the Radar example:

(a) The task was identified by the characteristics of the weapon, since the weapon identified the nature of the target and so disclosed its characteristics and identified the nature of the operational employment of the ship. An alteration to the weapon or a change in weapons (such as from rifles to missiles) alters the requirement on the Radar. The documentation provided in the model will clearly indicate any need for change in the design of the Radar.

(b) The operating requirements, with time, environment, and failure definitions, described the equipment adequately to identify technological areas where problems may exist.

(c) The model identified the reliability requirement, or at least laid the groundwork for such identification. It will assist in reliability and maintainability prediction by defining the equipment and anticipated stress levels.

(d) It will be used to design test and demonstration programs.

(e) During the entire development, it provides management visibility of the objective and the progress toward achieving that objective.

5. PERSONNEL AS A SYSTEM

The impact of personnel at every stage in the development of a system cannot be ignored. People design, build, operate and maintain the equipment. In many systems the subjective evaluation of the information provided by the display initiates the succeeding operation. In other systems, the adequacy with which maintenance is performed has a marked influence on the success or failure of the equipment.

The modern "black box" concept in equipment design has brought the designer face to face with the human operator problem. As he has to consider the characteristics of electronic "black boxes" so must he consider the human "black box". Each unit in a system will accept only certain inputs and emit only certain outputs and each in turn will operate satisfactorily only when used within given tolerances. The human component is no exception. In order to obtain reliable human performance in a man-machine system, the man must be able to work within his characteristic tolerances. The design of the equipment he operates must match his impedances at both input and output stage.

As a "black box", man can be represented in the system as a system element as shown in Figure 3-23 to make the system complete. We must, in fact, consider the role of man in the circuit. The effect of man on the design process and his relationship to the reliability of the system will be discussed later. (Chapter 14).

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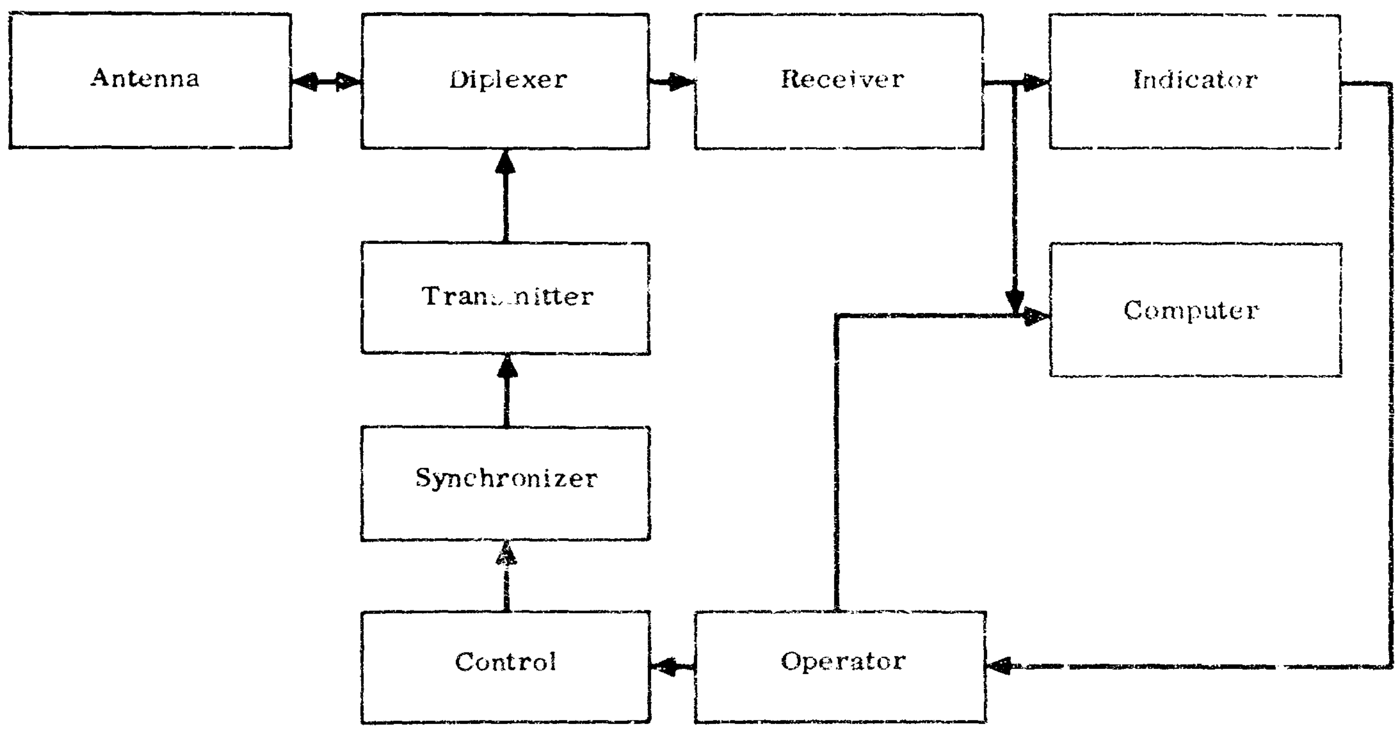
THE "COMPLETE" SYSTEM



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Chapter 4

PROBABILITY

Chapter 4

PROBABILITY

Our purpose in this section on probability is to acquaint you with the basic ideas of probability underlying the analysis of reliability. Our goal is not to convert engineers into statisticians, but rather to create a common ground for the efficient exchange of ideas concerning reliability.

The word probability is used loosely in our daily conversation and we know vaguely what it means. We talk of the probability of winning a game of cards or dice or a football game, the probability of its raining tomorrow, or the chance of a person living to be so many years old. In all these cases we are interested in a future event, of which the outcome is uncertain, and about which we want to make a kind of prediction. We would like to be able to devise a way of measuring the probability of an event - not only to determine its probability, but also to compare the probability of different events.

Historically, probability theory has had a strong relationship with games of chance, i.e., gambling, such as roulette, dice, poker, bridge, and black jack (twenty one). The one common characteristic in all these games of chance is the unpredictability of what happens on a given deal or a given turn of the wheel, i.e., on a given trial. However, as is known by any individual who has played any one of these games, there is regularity, and hence predictability, in the course of a large number of trials. Probability theory is, in general, concerned with the predictability of occurrences in a large number of trials, i.e., predictability "in the long run" or "on the average."

There are a large number of areas in which the characteristics - unpredictability during a given trial and predictability over a large number of trials - can be found. Probability theory has found an application in each one of these areas. The diversity of application of probability theory can be illustrated by listing some of the areas in which this theory is used.

1. Theoretical Physics: Statistical thermodynamics and quantum mechanics.

2. Nuclear Reactor Technology: Atomic Bomb development and critical sizes of nuclear engines.

3. Communication Theory: Telephone trunk lines and RF communication links.

4. Insurance: Life insurance and automobile accident insurance.

5. Medical Research: Genetics and theory of epidemics.

6. Theory of Learning

1. SIMPLE EVENTS

1.1 DENOTATION OF PROBABILITY

Since the term probability is applied to so many different events, it seems that one can hardly give it a definite meaning without some simplification. Later on we will see that we must extend the definition to include more complex situations in order to have a useful theory. So, taking fundamentals first, let us see how much we may already know about a method of assigning numbers to the likelihood of chosen events. Consider the simple experiment, the tossing of a coin. On a single toss of the coin, there are only two outcomes - heads or tails. Everyone will agree that if the coin is "honest," i.e., uniformly and symmetrically made, and if the tossing is "fairly done," there is no reason to expect the appearance of a head any more than the appearance of a tail. In everyday language, we say that "the coin has 1 chance in 2 of falling heads"; in technical language, we say that "the probability of heads is 1/2." In symbols, we write:

$$P\ (H) = 1/2$$

Similarly, in the tossing of a die, the face with six dots has 1 chance in 6 of landing on top; for it is assumed that the die is well made, thrown "fairly," and there is no reason for expecting any one face to turn rather than any other. We say that "the probability of 6 dots on top is 1/6." In symbols:

$$P\ (6) = 1/6$$

Likewise, when we take a card from a well-shuffled bridge deck, we have:

$$P\ (A) = \text{[illegible]}/52$$

1.2 FAVORABLE OUTCOME

Now, as an experiment, consider a 10-ticket draw for a prize. A name is written on each of 10 tickets, the tickets are then thoroughly mixed in a bag, and 1 ticket is drawn. The person whose name appears on the ticket so drawn is the winner.

If Susie's name appears on just 1 ticket, her chance of winning the prize is 1 in 10, since all outcomes in the drawing are "equally likely," that is, one of the 10 tickets shall be drawn, and there is no reason for expecting any 1 ticket to be drawn rather than any other. Thus,

$$P\ (S) = 1/10$$

Similarly, if Susie's name appears on 7 tickets, her chance of winning is 7 in 10, and

$$P\ (S) = 7/10$$

The general idea is that of separating from the whole set of equally likely outcomes, the special subset of favorable outcomes. We use the term "set" to speak of a group of anything with a particular characteristic, as the "set" of all American males. We use the term "subset" to mean a group completely within the set, with some other characteristic as the subset of "red-haired American males."

The probability of a favorable outcome is assigned by the following rule:

$$P\ (\text{favorable outcome}) = \frac{\text{number of favorable outcomes}}{\text{number of possible outcomes}}$$

This method of assigning to a favorable outcome a measure, or number, called its probability, has an immediate consequence, for if there are no favorable outcomes in the set of possible outcomes, then

$$P\ (\text{favorable outcome}) = 0$$

and, if all possible outcomes are favorable, then

$$P\ (\text{favorable outcome}) = 1$$

It follows that

$$0 \leq P\ (\text{favorable outcome}) \leq 1$$

that is, the probability of a favorable outcome lies within the range of numbers from zero to 1. For if a favorable outcome is certain to happen, its probability is 1; if it is certain to fail, its probability is 0; in every other case its probability must be between 0 and 1.

Another consequence of this method, since every outcome must be either favorable or unfavorable, is

P (favorable outcome) + P (unfavorable outcome) = 1

1.3 NUMERICAL BASIS

The definition of probability is based on a count of the number of possible results of a trial. Since there are six possible outcomes of a throw of a single die, the probability of any one number occurring is one sixth, assuming no bias. In general, if an event can occur in m ways and can fail in n ways, the probability of its occurrence is m/(m + n), provided the ways are exhaustive, equally likely, and mutually exclusive.

The concept "equally likely" is basic; it can play the role of the undefined element. Indeed, it is quite difficult to define the term "equally likely" without using the word probability. The term can be described as being the lack of any bias favoring one way over another in the random trial.

The ways are "mutually exclusive" if, when one is known to occur, the other is known not to occur. For instance, if the event is the drawing of a single card from a deck and obtaining an ace, there are four mutually exclusive ways of doing it: by drawing an ace of spades, hearts, diamonds, or clubs. If a single card is drawn and it is the ace of spades, it cannot be the ace of another suit. Here the ways are equally likely if the drawing procedure is not biased in favor of any one card. The probability of drawing an ace is 4/52 under these conditions.

1.4 DEFINITIONS OF RELATED TERMS

Some of the terms which were used in the definitions of probability and some other terms which will be needed later are defined as follows:

1. Exhaustive: As used in the definitions of probability, the term "exhaustive" means that all possible ways for an event to happen are included. The reasons for this restriction in the definition should be obvious.

2. Trial: Each attempt under a certain set of rules to produce an event A (where the outcome of the event A is uncertain) is a trial. Thus, each repeated throw of dice in a game of dice is an attempt to make one's point. One usually speaks of a random trial. The term "random" implies "without bias."

3. Independent Trials: If the outcome of one trial does not influence the outcome of a subsequent trial, the two trials are said to be independent. Each throw of dice in a dice game meets this criterion. However, the drawing of cards from a deck without replacement does not meet it, since the number of ways an event (drawing a specified card, for example) can happen changes with each drawing.

4. Conditional and Unconditional Probabilities: The conditional probability of an event is encountered when information about the occurrence of some other event is available. If one is informed that a certain event has occurred, does this tell him anything about the probability of the occurrence of another event? Knowing that B has occurred, what is the probability of A occurring? If the events are dependent, the knowledge that one has occurred does modify the probability of the other, and this probability is conditional. If no information is available as to the result of an event on a previous trial, the probability is unconditional.

2. COMPOUND EVENTS

Sometimes the problem requires that a set of outcomes be considered a single event. The problem of throwing a six each time on two successive trials, and the problem of drawing four aces on successive trials without replacement are compound events.

The determination of the probability of success in these two cases requires some refinement to our method of determining possible outcomes.

2.1 SIMPLE COMBINATIONS:

Expressions of the form "A or B" use the word "or" in two different ways: (1) in the exclusive sense, which connotes "A or B, but not both" (e.g., a coin falls "heads or tails"); (2)

in the inclusive sense, which connotes "A or B or both" (e.g., "The weather looks as if it may sleet or snow.") Ordinarily, the context is a sufficient guide to the intended meaning. Whenever the expression "A or B" is used in referring to events, we will always use the inclusive "or"; in other words, event "A or B" means "A or B or both". This inclusive "or" is defined in probabilistic language as a "union" of sets.

The idea of simultaneous membership in two sets is connoted in our use of "and" when we talk about events. Thus, if events A and B are subsets of a set, then "A and B" is their "intersection". that is, the event "A and B" contains those sample elements that belong to both A and B.

By using our definition of probability (2.2), three rules are needed for the calculation of the probabilities of compound events. Let E and F denote events; then, we want to know the probabilities of the following events derived from them:

a. The event "not E" (E does not occur). (or "not F")
b. The event "E or F" (either E or F or both occur).
c. The event "E and F" (both E and F occur).

For example, the event "E" may be "we get a 6", the event "F" may be "we get a 5". "Not E" is simply "not getting a 6" (getting any of the faces from 1 to 5). "E or F" is "getting a 5 or a 6". "E and F" is impossible for a single throw.

Rule 1. The probabilities of the events "E" and "not E" satisfy the equation.

$$P(\text{not } E) = 1 - P(E)$$

Example - Three coins are tossed. What is the probability of getting at least one head.

Solution - Since the question as stated really asks what is the probability of getting one, two, or three heads, it can be solved more simply by computing the probability of getting 3 tails (0 heads). There are eight equally likely outcomes (HHH, HHT, HTH, THH, HTT, THT, HTT and TTT). Only one of these (TTT) corresponds to the requirement of three tails. The probability of this is 1/8. This is "not E". The probability of E (at least one head) = 1 - P (Not E) or 7/8, hence P(E) = 7/8.

Rule 2. If two events E and F are mutually exclusive, then

$$P(E \text{ or } F) = P(E) + P(F)$$

Example - What is the probability that a card drawn at random from a deck of cards is either a heart or the queen of spades. Call E the event "heart" and F the event "queen of spades". By our definition

$$P(E) = \frac{13}{52} \text{ and } P(F) = \frac{1}{52}$$

By rule 2

$$P(E \text{ or } F) = \frac{13}{52} + \frac{1}{52} = \frac{14}{52} .$$

Rule 3. If E and F are independent events, then

$$P(E \text{ and } F) = P(E) \times P(F)$$

Example - From a deck of cards, two cards are drawn at random, successively; the first being replaced before the second is drawn. What is the probability that the first is a heart and the second is not a king. If E denotes "a heart" and F denotes "not a king".

$$P(E) = \frac{13}{52}, \quad P(F) = \frac{48}{52}$$

By rule 3

$$P(E \text{ and } F) = \frac{13}{52} \times \frac{48}{52} = \frac{12}{52}$$

2.2 COMPLEX COMBINATIONS

2.2.1 Conditional Probability: To introduce the notion of dependent events consider the following example:

> An urn contains 3 red balls and 2 black balls. Two balls are drawn in succession without replacement. If the first ball drawn was black, what is the probability that the second ball drawn will be red?
>
> Solution: Since we know the first one was black, we are actually in a new situation, - we have an urn containing 3 red balls and 1 black ball; hence by definition, $P(R) = 3/4$.

If we focus our attention on the event "getting a red ball", it is clear from the example that the probability of this event depends upon the information one has at hand. The probability usually isn't written as P(R) but rather P (getting red given that black has occurred), or symbolically $P(R|B)$. This probability $P(R|B)$ is called the "conditional probability of getting a red ball on the second draw, given that a black one was drawn on the first draw."

We saw that by taking into account what actually was happening, $P(R|B)$ was easily calculated. Another way of calculating $P(R|B)$ is the following:

Number the balls r_1, r_2, r_3, b_1, b_2; then list all the equally likely outcomes of drawing two balls from the urn when the first ball is not replaced. The 20 equally likely cases are:

r_1, b_1	r_2, b_1	r_3, b_1	b_1, b_2	b_2, b_1
r_1, b_2	r_2, b_2	r_3, b_2	b_1, r_1	b_2, r_1
r_1, r_2	r_2, r_1	r_3, r_1	b_1, r_2	b_2, r_2
r_1, r_3	r_2, r_3	r_3, r_2	b_1, r_3	b_2, r_3

Since the first ball was found to be black, the <u>equally likely outcomes</u> for the second ball being red are only those 8 among 20 original equally likely cases that have black in the first place; and the favorable cases for the second being red are those among the 8 equally likely cases with red in the second place. So, we have

$$P(R|B) = 6/8 = 3/4.$$

More generally, we have the following rule for calculating the probability of dependent events.

<u>Rule 4</u>. If E and F are dependent events (i.e., the result of event F depends on the results of an earlier trial of which event E is a possible outcome), then

$$P(E \text{ and } F) = P(E) \times P(F|E)$$

or inversely $P(F|E) = \dfrac{P(E \text{ and } F)}{P(E)}$

2.2.2 <u>Events not Mutually Exclusive</u>: In the example under Rule two the events were mutually exclusive. That is the success of event E "drawing a heart" precluded event F "drawing the Queen of Spades." They both couldn't happen on the same draw. Suppose the question had been, what is the probability of drawing a heart or a queen from the deck? In this case the probability of event E, "drawing a heart" is $P(E) = \frac{13}{52}$. The probability of event F, "drawing a queen" is $P(F) = \frac{4}{52}$. But the probability P(E or F) is not $\frac{13 + 4}{52}$ since one event (the Queen of Hearts) is common to both. The events are not mutually exclusive. To compute the probability of "either a heart or a queen" the ratio of the number of hearts plus the number of queens minus the number of queens of hearts is taken to the total number of cards

$$P(E \text{ or } F) = \frac{13 \text{ hearts} + 4 \text{ queens} - 1 \text{ queen of hearts}}{52 \text{ cards}} = \frac{16}{52}.$$

Rule 5. If E and F are not mutually exclusive, then P(E or F) = P(E) + P(F) - P(E and F).

2.3 SUMMARY

The probability of a simple event was defined in the ratio of successful outcomes to possible outcomes. The probability of a compound event was shown to be equally the ratio of successful outcomes to possible outcomes where the outcomes are described in somewhat more complicated ways. The five rules given are adequate to compute the probability of any combination of events, provided the probabilities of the individual events can be determined. To facilitate computation certain mathematical techniques may be employed.

3. BINOMIAL PROBABILITY DISTRIBUTION

3.1 LARGE NUMBERS OF TRIALS:

Consider the following experiment: Ten coins are tossed. What is the probability that exactly two of them are heads? This simple problem is complicated somewhat by the fact that the number of equally likely outcomes and outcomes favorable to an event is large, and enumeration of them is impractical. For example, if we tried to list the equally likely cases we would have

HHHHHHHHHH, HHHHHHHHHT, HHHHHHHHTH, HHHHHHHTHH,

..., HHHHHHHHTT, HHHHHHHTTT, ...,

and so on. To compute this probability, we can reason as follows: Each coin has two possible outcomes, heads or tails, and the occurrence of either of these to one does not affect what happens to the others. Using the basic principle that if event E can occur in m ways and F in n ways then the event "E and F" can occur in m x n ways (by rule 3) we can determine that there are altogether 2 x 2 x 2 x 2 x 2 x 2 x 2 x 2 x 2 x 2 = 2^{10} equally likely outcomes.

But 2^{10} = 1024 and it is no longer practical to list these in order to look through and pick out the outcomes favorable to some event.

Looking at the possible outcomes we can reason that there is only one of the combinations that shows no heads (TTTTTTTTTT). The number of combinations that yields one head are 10, a head in any one of the ten positions. Going one step further, to determine how many ways two heads can show, we know there are ten ways one head can show. If one head has shown, there are nine ways a second can show. The product of 10 x 9, then, gives us the total number of ways two heads can show. Since we make no distinction between H(1)H(2) TTT.... and H(2)H(1) TTT.... each successful outcome has been counted twice. So the number of combinations that yield two heads

$$\binom{10}{2} \text{ is } \frac{10 \times 9}{1 \times 2}.$$ The notation $\binom{10}{2}$ is presently used in statistical work, replacing the symbol you probably learned $({}_{10}C_2)$.

Following the reasoning to comput the number of combinations yielding three heads, we can say that if 2 heads have shown, there are 8 remaining coins leaving 8 ways the third coin can show. So there are 10 x 9 x 8 possible ways 3 coins out of 10 can be heads. Again there are duplications, in this case 2 x 3 or 6. The number of discrete combinations is $\binom{10}{3} = \frac{10 \times 9 \times 8}{1 \times 2 \times 3}$.

Continuing the reasoning we can state that

$$\binom{10}{7} = \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4}{1 \times 2 \times 3 \times 4 \times 5 \times 6 \times 7}$$ is the number of combinations in which 7 heads show. If we compute the number of combinations in which 3 tails show, we find $\binom{10}{3} = \frac{10 \times 9 \times 8}{1 \times 2 \times 3}$.

Since 3 tails is the same as 7 heads, these should give the same result $\binom{10}{3} = \frac{10 \times 9 \times 8}{1 \times 2 \times 3} = \binom{10}{7} = \frac{10 \times 9 \times 8 \times \cancel{7} \times \cancel{6} \times \cancel{5} \times \cancel{4}}{1 \times 2 \times 3 \times \cancel{4} \times \cancel{5} \times \cancel{6} \times \cancel{7}}$.

3.2 DEFINITION

The product of all the integers from 1 to n is termed "n factorial" or n!. Using this notation, the term $\binom{n}{r}$ can be written $\frac{n!}{r!(n-r)!}$.

For the term $\binom{10}{2}$ this becomes

$$\frac{10 \times 9 \times (8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1)}{1 \times 2 \times (1 \times 2 \times 3 \times 4 \times 5 \times 6 \times 7 \times 8)} = 45,\text{ noting}$$

that the portions in parenthesis cancel.

The probability of two heads in ten coins is then $\frac{45}{1024}$ = .044.

3.3 BINOMIAL THEOREM

This can be reached in another way. The number of ways (r) successes and (n-r) failures can occur in n events is $\binom{n}{r}$ as defined above. The probability that an individual success (heads) will occur is p, in this case 1/2.

The probability that the event will occur in exactly this way,

(r) successes (heads) and (n-r) failures (tails) is

$\binom{n}{r} p^r (1 - p)^{n-r}$ or $\binom{n}{r} p^r q^{n-r}$ where q = 1 - p.

This term, called the binomial probability distribution, is mathematically the same as the computation used previously. Tables (1) are available that tabulate the terms for values of n up to 50 for any value of p between 0 and 1 in increments of .01.

3.4 BINOMIAL AS A PROBABILITY DISTRIBUTION

The term probability distribution refers to the probability of achieving various events.

The distribution of expected outcomes is proportional to the probabilities of the individual outcomes. For the 10 coins, the number of ways in which favorable outcomes can occur are:

Favorable Outcome	Ways	Probability
0 Heads	1	.001
1 Heads	10	.010
2 Heads	45	.044
3 Heads	120	.117
4 Heads	210	.205
5 Heads	252	.246
6 Heads	210	.205
7 Heads	120	.117
8 Heads	45	.044
9 Heads	10	.010
10 Heads	1	.001
	1024	1.000

Plotting this on a histogram provides this view of the binomial probability distribution (Figure 4-14).

4. EMPIRICAL PROBABILITY

4.1 FUNDAMENTAL CONCEPT

The previous discussion of the Binomial Probability distribution illustrated the fact that the probability that exactly r successes would be observed in n trials could be expressed as

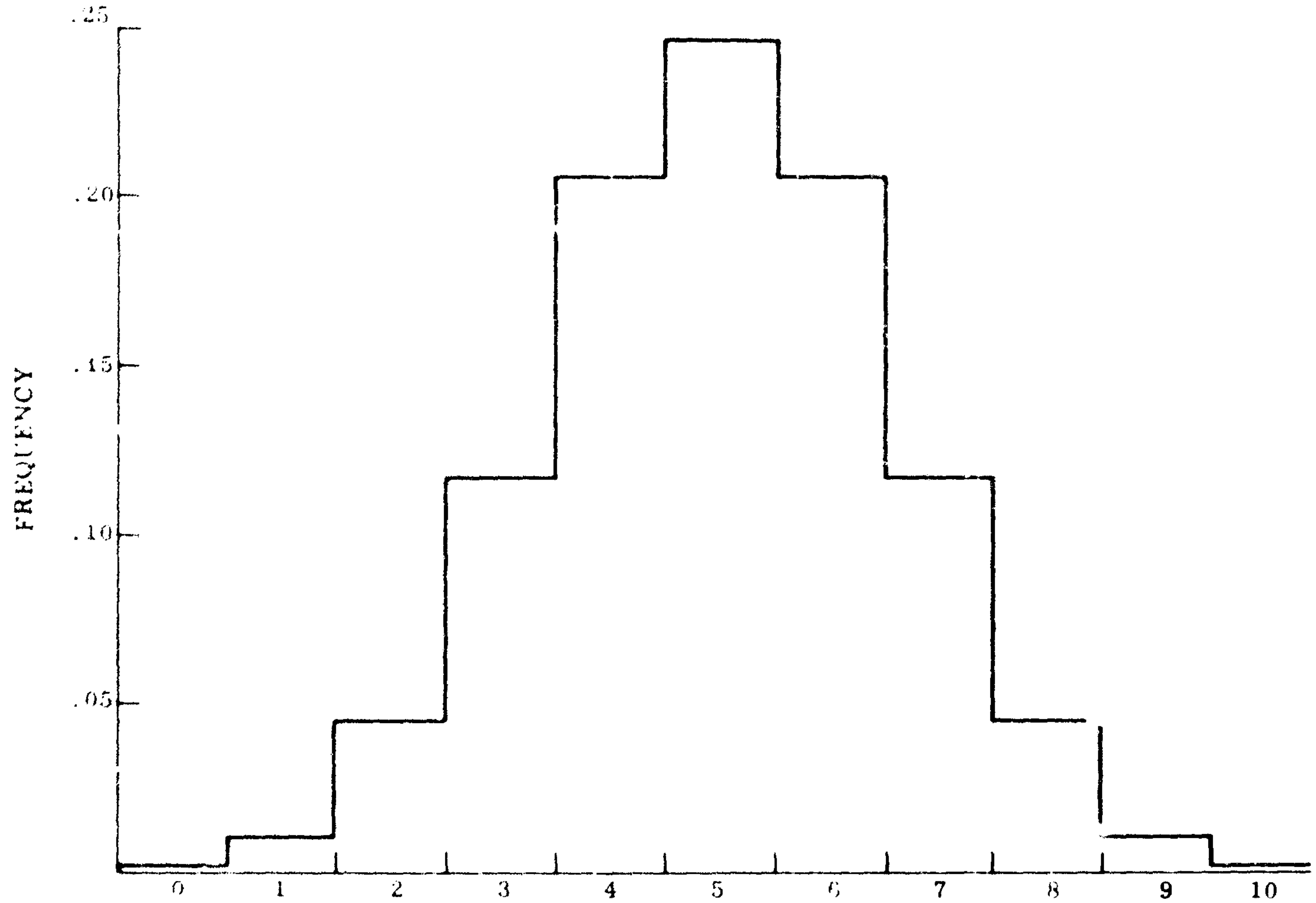
$$P\ (X = r) = \binom{n}{k} p^r q^{n-r}$$

where $q = 1 - p$ and p is the constant probability of success on each trial. In previous discussions, the probability, p, of success on each trial was determined by deduction. However, this binomial distribution form can also be used when p is determined analytically, say by an integration, and turns out to be an irrational number. Even when p is unknown - the only requirement is that p be constant for each of the n trials. The discussion of Empirical Probability relates to the problem of what can be done when p is unknown.

4.2 DEFINITION

In the events we have been discussing we have been able to compute the probability of an event by enumeration. We could compute the number of possible outcomes and of these identify those we considered favorable. In a large class of events, however, we cannot identify or count the equally likely outcomes. Can we predict whether or not it will rain on the Fourth of July. There are two possible outcomes, rain or no rain, but we cannot

BINOMIAL DISTRIBUTION - 10 COINS



say they are equally likely. If we had maintained records of rain in Washington over the last hundred years we could identify the number of times event E "rain in Washington on the Fourth of July" had occurred. From this we could make an estimate of the probability of its occurrence this fourth.

The probability given by our previous definition is called "a priori," or prior, probability because the probability of an event can be deduced directly without actual experimentation, e g., the probabilities associated with a die are deduced directly from observing the uniformity and symmetry of the die and the "fairness" of its tosser. On the other hand, the following definition requires that enough experimentation can be performed in order to study the relative frequency of the occurrence of an event; in fact, henceforth, we will confine our discussion to probabilities of events that can only be determined by repeated trials and the use of this definition. Probabilities defined in this way are called empirical or experimental. Thus we have assumed that there is a number which gives the correct probability of an event, although one cannot say what that number is. Furthermore, we will assume that the empirical probability obeys all the rules developed for "a priori" probability.

If whenever a series of many trials is made, the ratio of the number of times the event E occurred to the total number of trials is nearly some constant p, and if the ratio is usually nearer to p when a longer series of trials are made, then we agree in advance to define the empirical probability of E as p.

4.3 THE ROLE OF "EMPIRICAL" PROBABILITY

Whenever the subject of tossing coins arises, everyone readily agrees that a priori probability of heads is 1/2. This, of course, is because they believe that the symmetry and uniformness of coins insure the equal likelihood of heads or tails -- which results in the value 1/2. As an example, let us consider tossing thumbtacks. When a thumbtack is thrown, it falls "point up" or else "point down", and even though it possesses symmetries and uniformness, it is very difficult (if not impossible) to assign a priori probabilities in this case. To find the probability of "point up", one would simple calculate the empirical probability of this event.

This was tried experimentally, a thumbtack being flipped 2750 times. Of these, the tack fell "point up" 2054 times. From this we can define the empirical probability of "that" thumbtack falling point up on any succeeding trial or series of trials as

.747. One can then define the Probability of 3 "points up" in 5 thumbtack tosses as $\binom{5}{3}\ (.747)^3\ (.253)^2$.

We will go into greater depth on the treatment and application of empirical results when we introduce statistics several lectures from now. The point being made here is that we can, with certain justification, apply the results of past trials to estimating the probability of success or failure of future trials.

4.4 ASSUMPTION OF EQUALLY LIKELY EVENTS

Probability deals with the prediction of future successes. Once a trial has taken place it becomes a statistic. It either succeeded or failed. Probability is no longer associated with that particular trial. The statistic, representing an event of the past, does however provide some information useful in the future. Having once conducted the trial we have some assurance that if exactly the same conditions are encountered on some future trial, the same results will be obtained. It is in the inexactness of the repetition of conditions that probability theory finds its place. In drawing from a deck of cards if the 23rd card from the top were drawn, this would be a certain card. If the deck were again ordered exactly as before and the 23rd card drawn, it would still be the same card. This is not a probabilistic study. Probability assumes that the card is drawn at random, that every card has an equal chance of being in the position selected. Probability theory assumes that there is a certain, but not necessarily known, distribution function describing all possible outcomes of the event.

4.5 VALIDITY OF PROBABILITY THEORY IN RELIABILITY ENGINEERING

In the operation of equipment, failures occur. These failures are caused by physical causes, such as wear, overstress, deterioration, contamination, etc. In some kinds of equipment these failures can be predicted fairly precisely. In others, they seem to occur randomly, at unpredictable times. Where they are predictable, the cause is soon known. Where they are not, evaluation of the failures indicate many different causes. From this we draw the conclusion that in the unpredictable case a large number of factors are at work, each causing some of the failures.

5. FAILURE DENSITY FUNCTIONS

5.1 EQUIPMENT FAILURES

In the testing of equipment, and in its operation, records have been kept of failures and operating times to failure. Histograms have been prepared showing the relationship between operating times and failures. Among others, the histograms shown in Figure 4-18 seem to occur with relatively high frequency. A histogram like this displays the distribution of times to failure and is called a "density function." Engineers have identified these distributions as characteristic density functions which describe, to a degree, the relationship of past failures to the incidence of the physical factors causing them. If this interpretation is true, then the histograms shown may be used as probability density functions describing the probability of failure with time. Later we will impose some severe restrictions on the use of these functions, but for now, we will say one can be identified.

5.2 USE OF PROBABILISTIC MATHEMATICS IN RELIABILITY

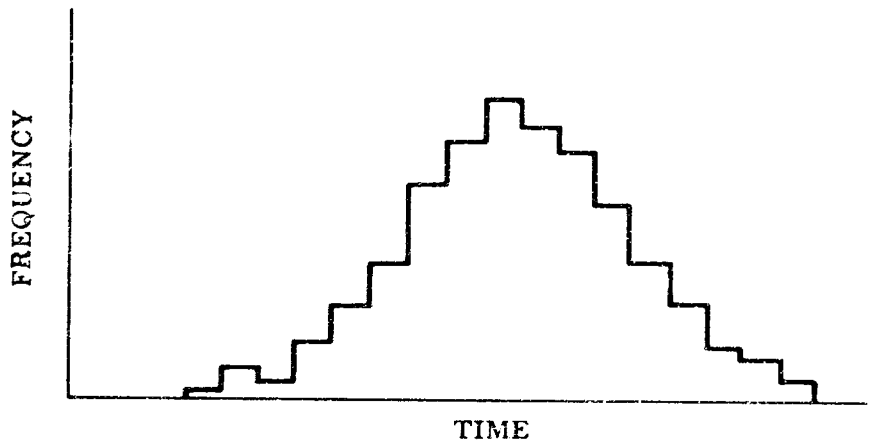
The dictionary defines reliable as trustworthy, suitable or fit to be relied on. Reliability, then, is the degree to which equipment may be trusted to do a job. Because of the apparent relationship to probability theory shown in testing, reliability has been defined as the probability that equipment will perform within specifications for a specified time when operating in a specified environment. When we use the term "within specifications," included in the meaning is "failure-free operation." In probabilistic language, reliability is the ratio of the subset of failure free operations to the set of all attempted operations. Probability theory, and its application to estimating the probability that a failure will occur, or will not occur, within a designated time, is one of the major mathematical tools of reliability engineering.

6. APPLICATION TO RELIABILITY COMPUTATION

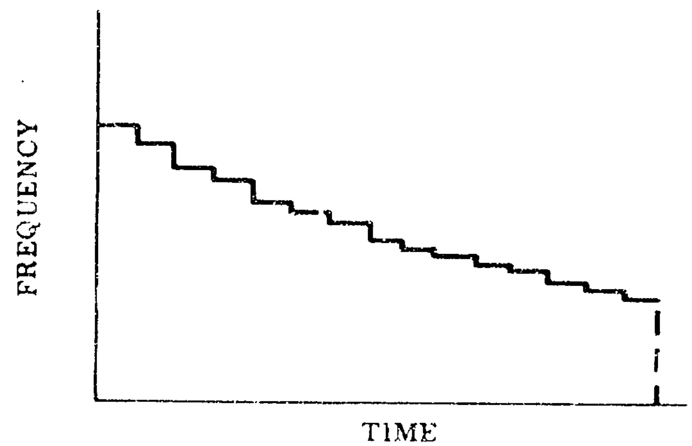
As we discussed in the last lecture, systems are not simple entities. They consist of a great many parts, each of which is subjected to different working conditions, environments, stresses. In attempting to evaluate the reliability of an equipment or system two approaches are available.

(1) Build some and test them, or

FAILURE FREQUENCY DISTRIBUTIONS



A



B

(2) Test the parts and combine the probability of success of all the parts in such a way as to determine the probability of failure of the assembled unit.

6.1 COMPLETE SYSTEMS

In the first approach, we use the test results to determine a single failure density function, the distribution of times to failure. The fraction of failures that occur prior to the time of interest, t_1, is used as the probability that a failure will occur prior to time t_1. We call this probability q_1. The number obtained by subtracting q_1 from 1, $(1-q_1)$, is the probability that no failure will occur prior to time t_1. This we have defined as our reliability.

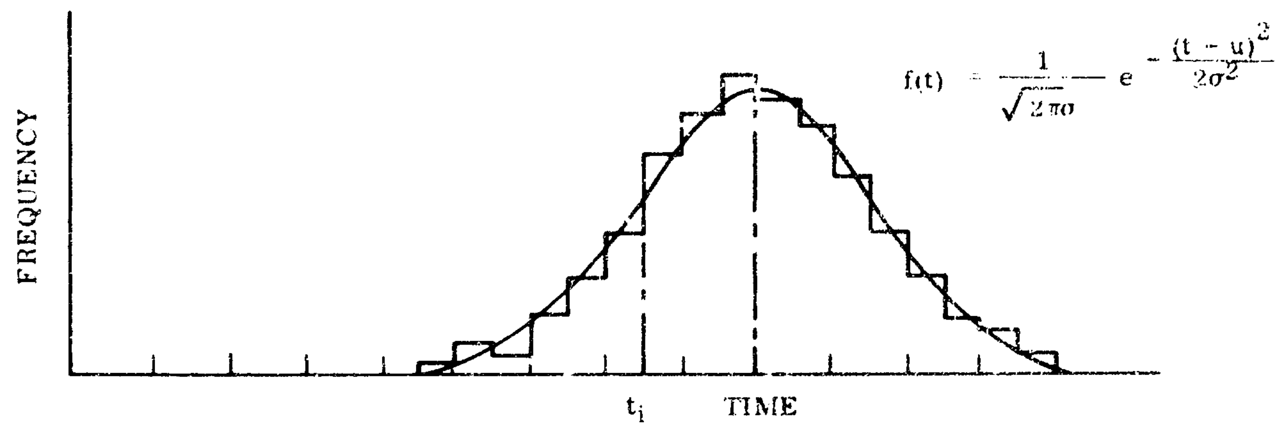
6.1.1 Two Useful Distributions: As mentioned earlier, two distributions have been found to occur most frequently. These distributions have been approximated by mathematical functions useful in computation of the reliability. For reasons which will become clear in the statistical section, we normally predict from the physical factors involved which distribution function should apply, fitting our data to the curve assumed. Two functions useful for this purpose are:

(a) Normal or gaussian
(b) Exponential.

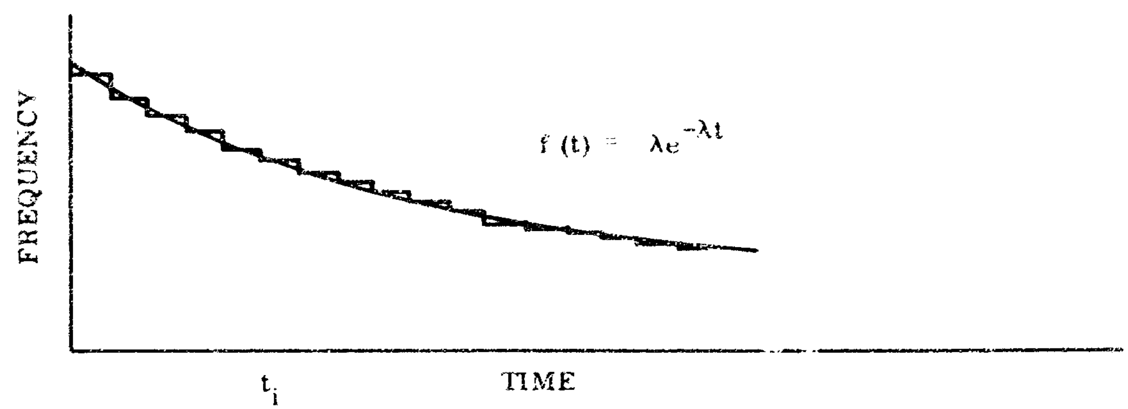
These are shown overlaid on the histograms of failure times in Figure 4-20. The curves show the (idealized) probability of failure at any time. The probability that the equipment will have failed by a time, t_1, is the aggregate of the probabilities that it fails at times prior to t_1, that is the area under the curve from $t = 0$ to $t = t_1$. Figure 4-21 shows the normal density function and its relationship to the reliability function. In A the hatched area shows the aggregate probability of failure to time t_1. This is the value q_1. The value $(1 - q_1)$ is plotted against time in B. This value is the reliability to time t_1.

6.1.2 The Normal (Gaussian) Function: This typifies the situation caused by wearout of a single part. It applies where the failure pattern is caused predominantly by the failure of one particular part, as for example in a pump with a bearing greatly overloaded or of poor quality. The probability of successful operation to time t_1 is the probability that that one part will operate to that time. In this case, variations in quality or loading cause minor deviations from a characteristic or mean

TWO DISTRIBUTION FUNCTIONS

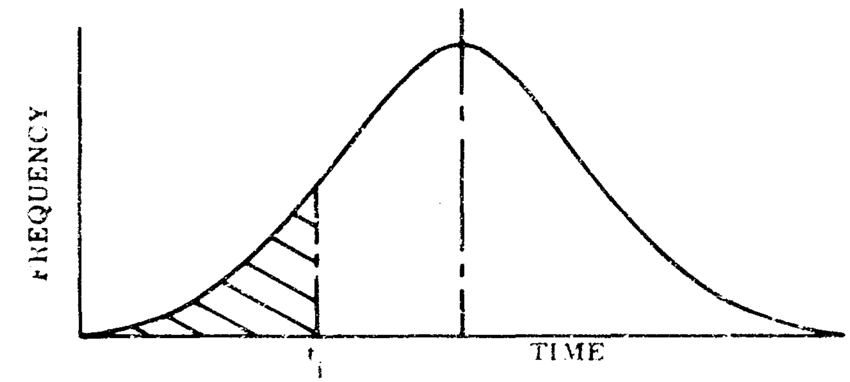


NORMAL DISTRIBUTION

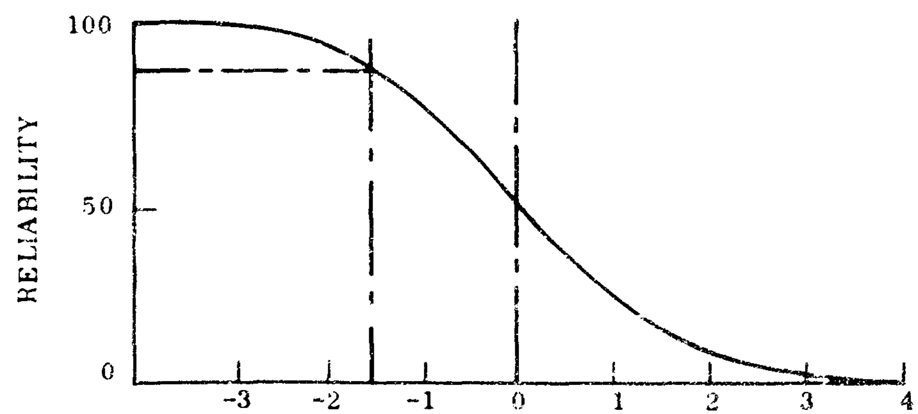


EXPONENTIAL DISTRIBUTION

NORMAL DISTRIBUTION



NORMAL DENSITY FUNCTION



NORMAL RELIABILITY FUNCTION

life. Very few failures occur at times greatly distant from that mean life.

The characteristics of this function are defined by two parameters. The mean life μ and the standard deviation σ: μ is the measure of central tendency, the average of the recorded lives; σ is the measure of dispersion from that average.

Tables of the ordinates of the normal curve and areas under the normal curve with mean zero and standard deviation 1 are published in most reliability books and many other books of mathematical tables (2). These can be used directly for reliability computations, entering with the value $Z = \frac{t - \mu}{\sigma}$.

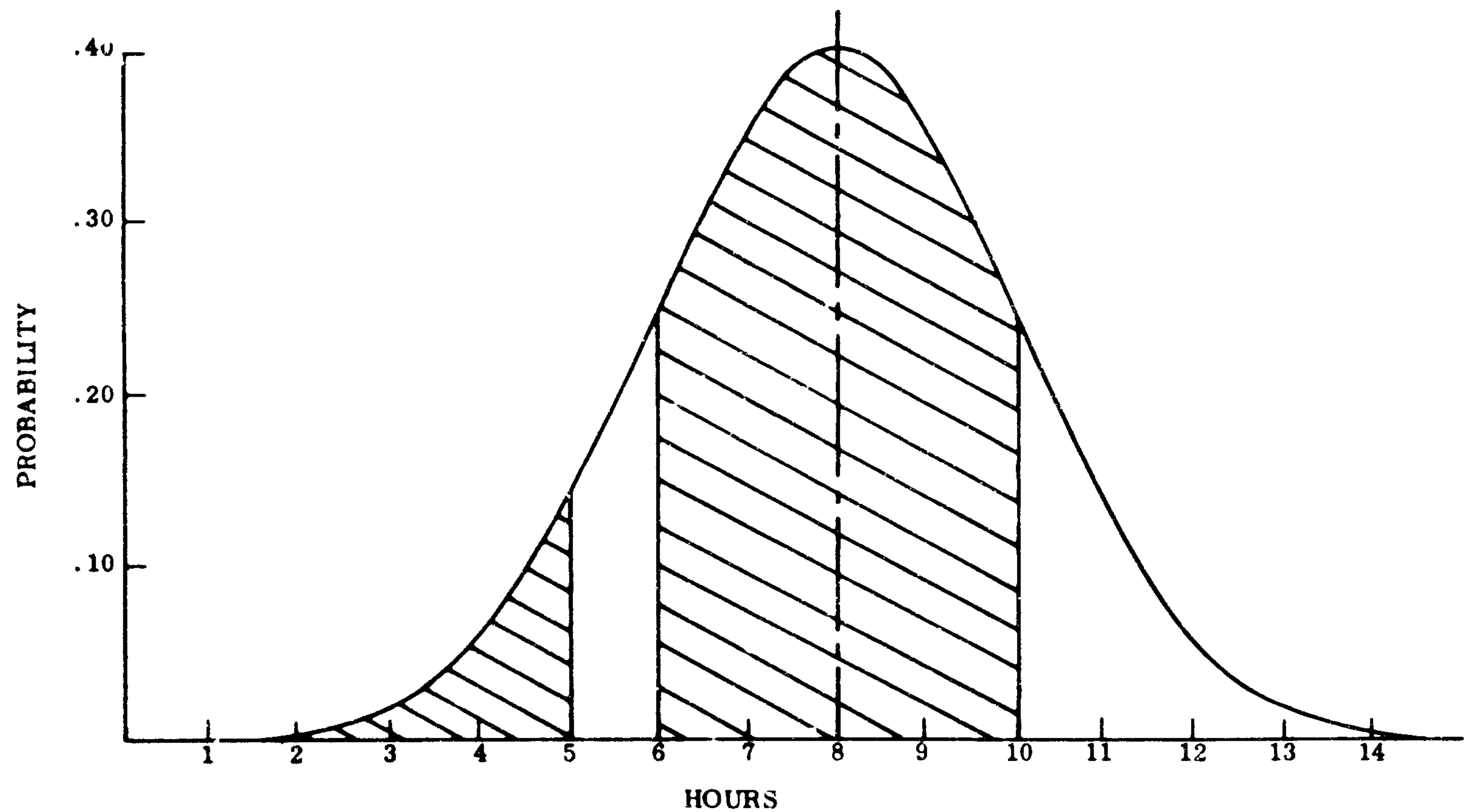
Example: For a part with mean life μ = 8 hours and standard deviation σ = 2 hours, find the probability that the part will continue to operate for 5 hours. $Z = \frac{5 - 8}{2} = -1.5$. From the table of areas under the normal curve for Z = -1.5 we find the portion of total area under the curve from $-\infty$ to -1.5 to be 0668. This is the probability that the part will fail by 5 hours. The reliability is one minus this value or 0.9332. (Figure 4-23).

Example: For the same part, find the probability that a failure will occur between 6 and 10 hours $Z_1 = \frac{6-8}{2} = -1$ $Z_2 = \frac{10-8}{2} = +1$.

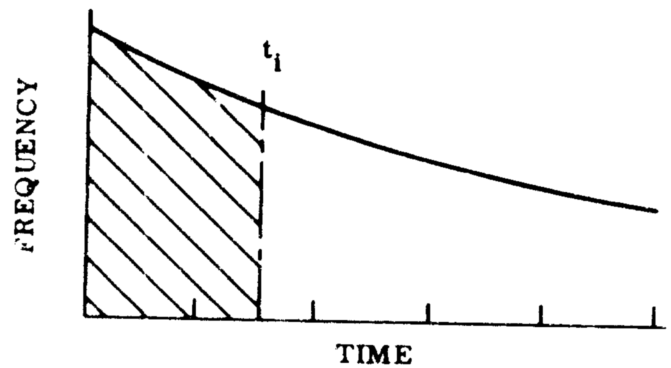
The areas under the curve are, for Z_1 = -1, area = .1587 for Z_2 = +1, area = .8413. The area under the curve between 6 and 10 hours is the difference or .6826. The probability that a failure will occur during this period is .6826.

6.1.3 Exponential Function: This typifies the "chance" failure rate function found to be evident in a large preponderance of situations. It appears to be typical of most electronic systems and numerous mechanical systems. It indicates a balanced design, in effect, where no single part (or few parts) failures predominate. The characteristic of the exponential distribution is that the probability of failure is constant for any equal periods of time. This constant probability is defined by a characteristic mean time between failure, MTBF. The density function, or distribution of times to failure takes the form of the negative exponential equation $\lambda e^{-\lambda t}$ where e represents the base of naperian or natural logarithms e = 2.71828 (Fig. 4-24). The reliability is again 1 minus the area to time t, so $R = e^{-\lambda t}$ where λ is the reciprocal of the MTBF ($\lambda = \frac{1}{MTBF}$) and t is the interval of time of operation of equipment. The symbol

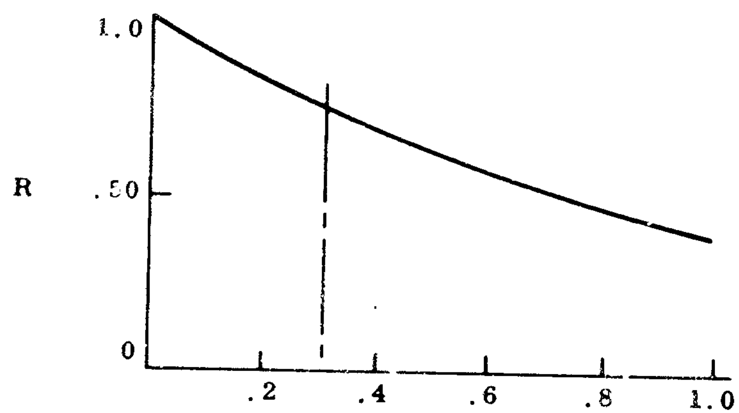
PROBABILITY OF FAILURE



EXPONENTIAL DISTRIBUTION



EXPONENTIAL DENSITY FUNCTION



EXPONENTIAL RELIABILITY FUNCTION

λ is defined as the failure rate. The characteristics of this function are completely defined by the one parameter, MTBF. If the value of this MTBF parameter (or its reciprocal, λ) is known then one can compute probabilities of failure occurrences during given intervals.

Example: The MTBF for a part is 100 hours. Find the probability that the part will fail in the first 10 hours of operation.

$$P(t_f \le 10) = \int_0^{10} \frac{1}{100} e^{-t/100} dt = 1 - e^{-10/100}$$

$$= 1 - e^{-0.1} = 1 - 0.905 = 0.095$$

The reliability of operation of this part over the 10-hour interval is $e^{-10/100} = 0.905$.

Example: The reliability of a part is known to be 0.98 over a 150-hour time of operation. Find its failure rate.

$$0.98 = e^{-\lambda \times 150}$$

$$\ln 0.98 = -\lambda \times 150$$

$$\lambda = \frac{-\ln 0.98}{150} = \frac{.02020}{150} = .000135$$

Example: A part has an MTBF of 100 hours. Compute the probability that this part will not fail in the time interval [100 hours to 200 hours] given that it operated successfully for the first 100 hours.

If we let A symbolize the event "no failure in the interval [100, 200]" and B the event "no failure in [0, 100]", the desired probability is seen to be a conditional probability, $P(A|B)$. According to the definition

$$P(A|B) = \frac{P(A \text{ and } B)}{P(B)}$$

Now, A and B is the event "no failure in the interval, [0, 200]".

$$P(A \text{ and } B) = e^{-200/100} = e^{-2}$$

$$P(B) = e^{-100/100} = e^{-1}$$

$$P(A|B) = e^{-2}/e^{-1} = e^{-1} = 0.368$$

One point that should be noted is that the reliability for a period of time equal to the MTBF is only .37. A second point is also of interest -- given 100 hours of successful operation, the probability of 100 future hours of successful operation can be computed on the same basis as 100 hours on new equipment. The same statement can be made if we consider an interval of 100 hours after 900 hours of successful operation. In particular, for the negative exponential case results from tests involving successfully used equipment rather than new equipment are still valid.

This type of result is unique to the negative exponential and is not applicable for Normal, Weibull, or other distributions of times to failure where the failure rate is not constant.

6.2 PREDICTING RELIABILITY OF SYSTEMS FROM RELIABILITY OF PARTS

6.2.1 Reasons for Prediction: Building equipment and testing it to determine reliability provides this result too late to influence the design. A designer would prefer to evaluate the reliability of the design before he spends money on production. This would permit him to make changes to his proposed design to meet the requirements at greatest economy. The alternative to testing the complete unit is determining the reliability characteristics of the parts that make up the unit and then, somehow, combine this information to ascertain the reliability of the assembled unit. This is the probability of a compound event, discussed earlier. The five rules presented at that time are the rules of combination of simple events to determine the probability of a compound event. The compound event is the reliability or probability of success for a certain time of the equipment. The simple events are the reliabilities of the individual parts.

6.2.2 Case 1, Series: If the successful operation of all the part is necessary for the success of the equipment, the multiplication rule applies. The probability of the successful outcome of all of a series or group of events is the product of all the individual probabilities of success. This is an application of our probability combination rule, Rule 3.

$$R_R = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times \dots \times R_N$$

This is like a chain. If any link breaks, the chain fails.

6.2.3 Case 2, Parallel: If the equipment will succeed if either of two (or more) parts perform successfully, then it will fail only if both (or all) parts fail. Using the multiplication rule (Rule 3) with rule 1.

$$R_E = 1 - (1-R_1) \times (1-R_2) \times \ldots \times (1-R_N)$$

6.2.4 Case 3, Series-Parallel: It is frequently the case that both series and parallel situations exist simultaneously in the equipment. To determine the reliability of the equipment, resolve each parallel situation into its equivalent reliability then the total may be treated as a series case.

7. SAMPLE COMPUTATIONS

7.1 SERIES CASE - NORMAL DISTRIBUTION

Normal or gaussian failure density functions. Assume an equipment E consisting of four parts (A,B,C,D) (Figure 4-28), in series, with the following characteristics.

	Mean Life μ	Standard Deviation σ
A	4	1
B	5	1.25
C	6	1.50
D	10	2.50

The individual density functions are given in Figure 4-29. The reliability of the equipment to time t = 2 is computed as follows:

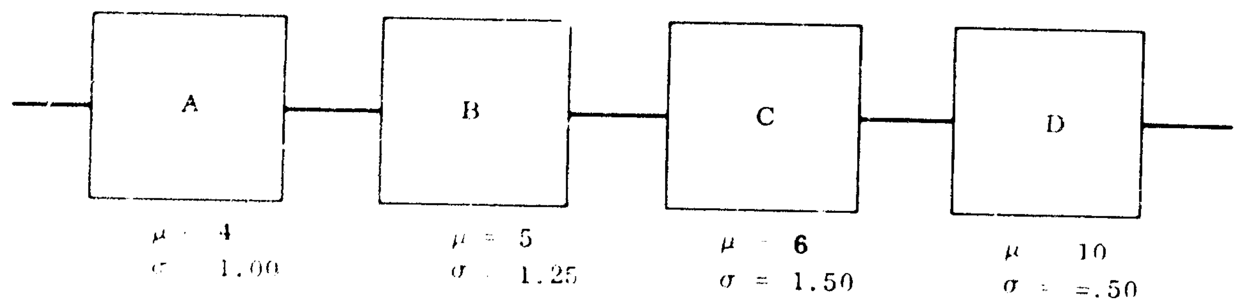
	$Z = \frac{t - \mu}{\sigma}$	Area	R
A	$\frac{2-4}{1} = -2.0$	.0228	.9772
B	$\frac{2-5}{1.25} = -2.4$	.0082	.9918
C	$\frac{2-6}{1.5} = -2.667$	.0038	.9962
D	$\frac{2-10}{2.50} = -3.20$	.0007	.9993

The reliability $R_E = R_A \times R_B \times R_C \times R_D$

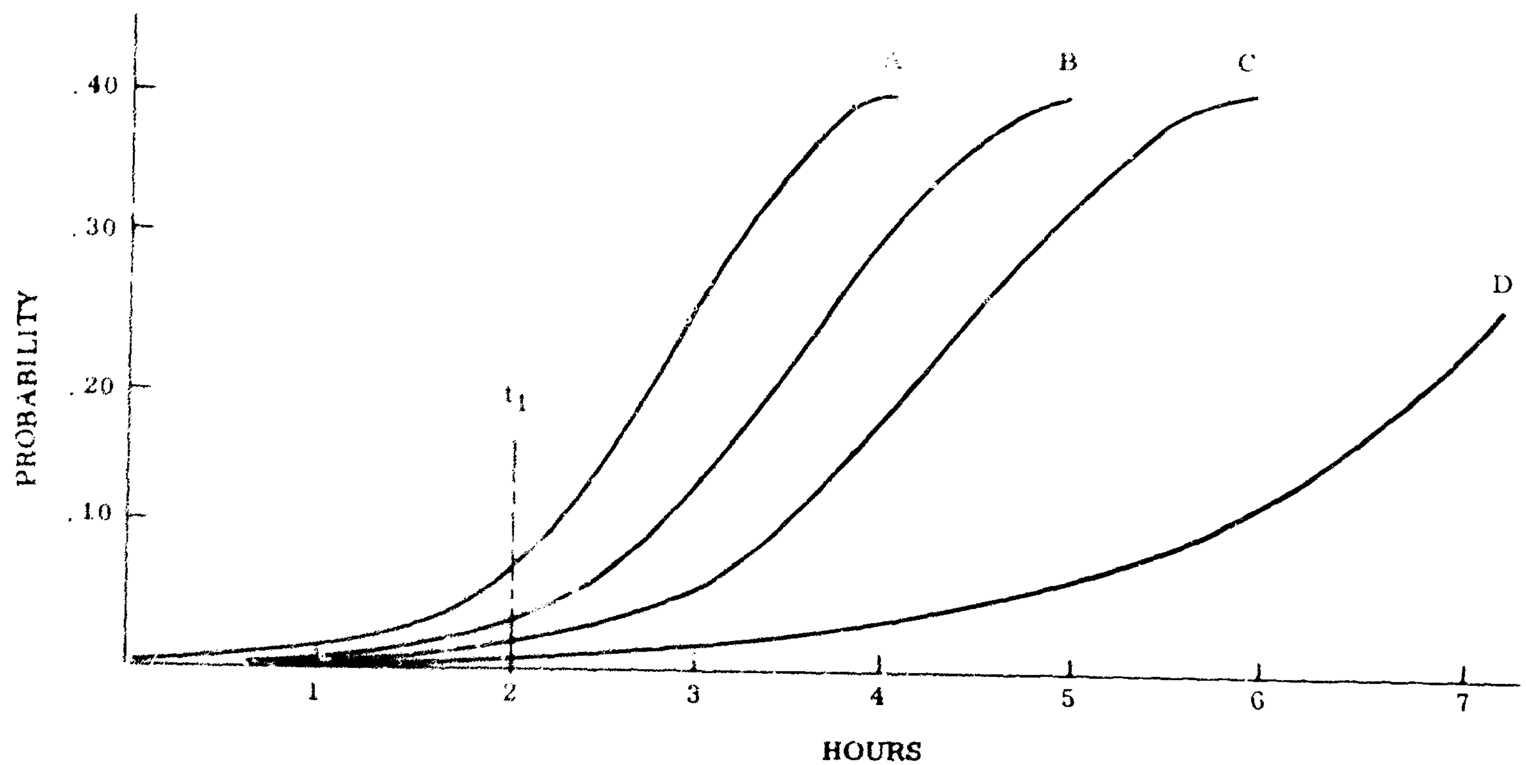
$$R_E = .9645$$

This, of course, assumes that all parts are new, starting from

SERIES COMBINATION



NORMALLY DISTRIBUTED TIMES TO FAILURE



time 0.

7.2 GENERAL SERIES CASE - NORMAL DISTRIBUTION

In the more general case, the parts have various operating times already accrued, as for example when the equipment is operated to failure, repaired and continued in operation. We might look at the reliability of the equipment for some other two hour period, say, from the 14th to 16th hours (Figure 4-31).

Where this situation obtains, the normal curves have to be redrawn to start each at the time the repaired part started operating, still with the same mean life and same standard deviation. The reliability for the two hour period in question is still the product of individual reliabilities. The probability that any part will fail during a particular period is the area under the normal curve for the period in question, obtained by subtracting the area under the tail of the curve ($-\infty$ to t_2).

Knowing that the equipment has not failed at time t = 14, implies each part has a conditional probability of failure, given that it has not failed at time t = 14. The conditional probability that the equipment will fail during the period 14 hours to 16 hours is the ratio of the area under the individual curves between 14 and 16 hours to the area under the curve from 14 hours to $+\infty$. In the case shown, the reliability of the equipment is found to be.

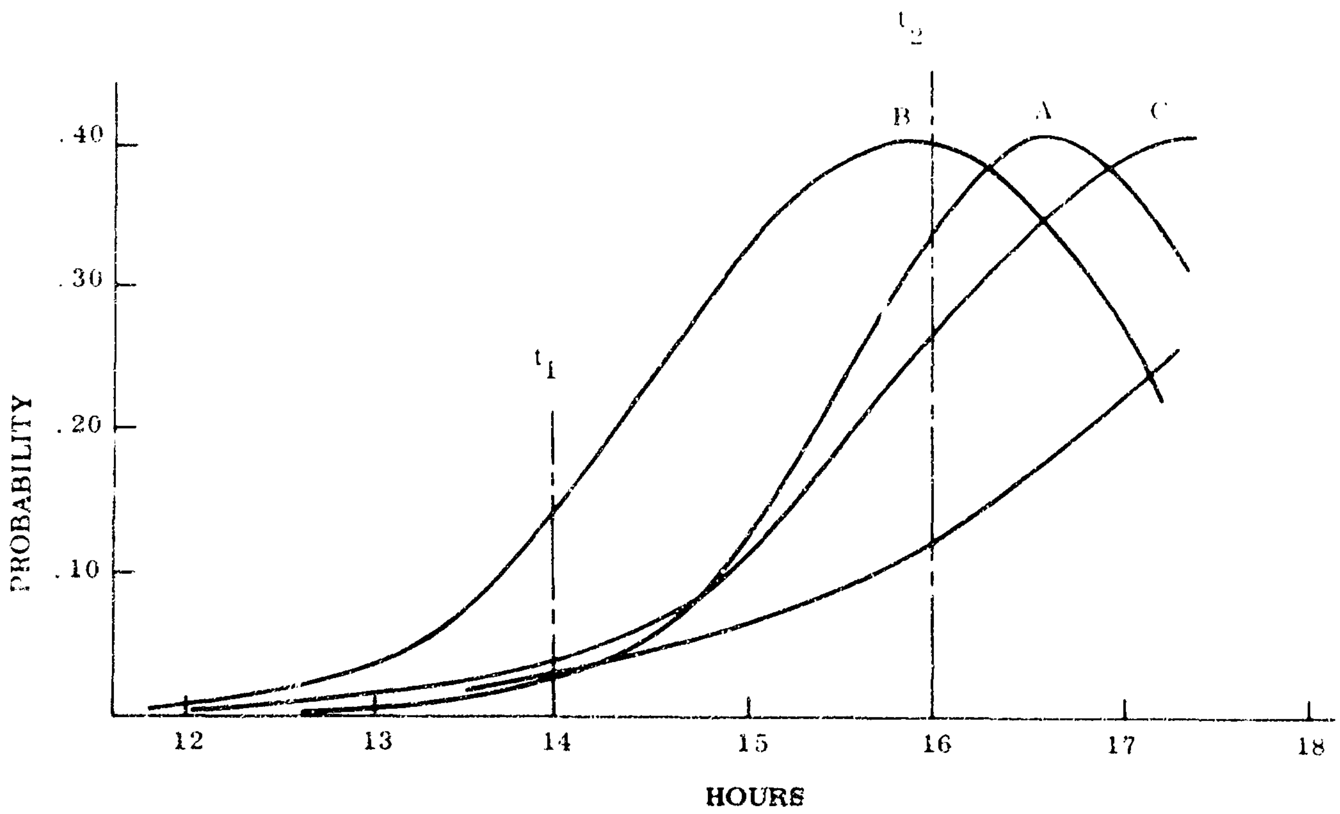
SERIES CASE - NORMAL DISTRIBUTION

TO FIND RELIABILITY OF EQUIPMENT E FROM TIME t = 14 to t = 16

	PART	A	B	C	D
1	time of last failure, hours from 0	12.6	10.8	11.4	9.6
2	mean life measured from last failure	16.6	15.8	17.4	19.6
3	$z = \frac{t-\mu}{\sigma}$ computed for 14 hours	-2.6	-1.34	-2.27	-2.24
4	$z = \frac{t-\mu}{\sigma}$ computed for 16 hours	-1.6	+.16	-.93	-1.44
5	Area under normal curve ($-\infty$ to 16 hours)	.0548	.5636	.1762	.0749
6	Area under normal curve ($-\infty$ to 14 hours)	.0047	.0901	.0116	.0125

NORMALLY DISTRIBUTED TIMES TO FAILURE

AFTER SEVERAL FAILURES



	PART	A	B	C	D
7	Difference	.0501	.4735	.1646	.0624
8	R	.9499	.5265	.8354	.9376
9	R_E	.3917			

7.3 SERIES CASE - EXPONENTIAL DISTRIBUTION

When the negative exponential distribution applies to the parts failure rates, the probability of failure is independent of prior operation. For any period of time t the reliability of the equipment for the serial case is the product of the reliabilities of the parts, that is

$$R_E = e^{-\lambda_A t} \times e^{-\lambda_B t} \times e^{-\lambda_C t} \times e^{\lambda_D t} \dots$$

$$= e^{-(\lambda_A + \lambda_B + \lambda_C + \lambda_D \dots)t}$$

The reliability of an equipment consisting of four serial parts with MTBFs, as before of 4, 5, 6 and 10 hours, for a 2-hour period, can be computed as follows:

Part	MTBF	$\lambda = \frac{1}{MTBF}$	$R = e^{-\lambda t}$
A	4	.25	.606
B	5	.20	.670
C	6	.183	.691
D	10	.100	.818
$\sum_{i=A}^{D} \lambda_i$		.733	

$$R_E = e^{-(\sum \lambda)t} = e^{-.733 \times 2} = e^{-1.467} = .230$$

7.4 SERIES PARALLEL CASE - EXPONENTIAL DISTRIBUTION

In the previous examples, it was assumed that the failure of any one component would cause equipment failure. If there are parallel components or series parallel combinations the principles of combination of probabilities discussed earlier apply. A computation will be performed for such a combination to explain the procedure. An equipment consists of four parts, (Figure 4-34) with part B such that a failure of B_1 would not constitute an equipment failure unless B_2 also failed. Likewise a failure of B_2 would not constitute equipment failure unless B_1 also failed.

We assume a negative exponential distribution of times to failure for all parts. The reliability of the equipment is the product of the reliabilities of each part A, B_1 and B_2, C and D, where B_1 and B_2 must be considered together.

	MTBF	λ	R(2-hours)
A	20	.05	.905
B_1	10	.10	.819
B_2	15	.067	.875
C	25	.04	.923
D	30	.033	.939

But the probability that both B_1 and B_2 fail is the product $(1 - R_{B_1}) \times (1 - R_{B_2})$. The combined reliability is 1 minus the product. Expanding the product gives $R_{B_1 B_2} = 1 - (1 - R_{B_1})(1 - R_{B_2})$

$$= 1 - 1 + R_{B_1} + R_{B_2} - R_{B_1} R_{B_2}$$

$$= R_{B_1} + R_{B_2} - R_{B_1} R_{B_2}$$

$R_{B_1} = .819$

$R_{B_2} = .875$

$R_{B_1} \times R_{B_2} = .716$

$R_{B_1 B_2} = .978$

The reliability $R_E = R_{B_1 B_2} \times R_A \times R_C \times R_D$

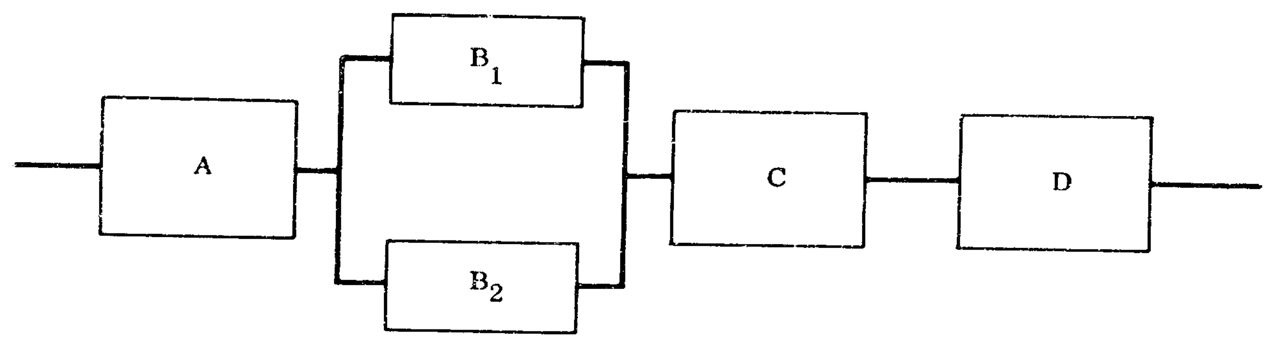
These last three terms may be combined as before to

$R_{ACD} = e^{-(\lambda_A + \lambda_C + \lambda_D)t}$

$= e^{-(.123)2} = .781$

then $R_E = (.978) \times (.781) = .752$

SERIES-PARALLEL COMBINATION



7.5 STANDBY PARALLEL CASE - EXPONENTIAL DISTRIBUTION

The foregoing example assumed both B_1 and B_2 operating simultaneously as, for example, two generators operating in parallel, where it is clear that one can handle the entire load without increasing the probability of its failure. Let us look at a slightly different situation, (Figure 4-36), two generators, one operating the other not operating unless the first fails, at which time it will be substituted for the first. Two switches, S_1 and S_2 have been added to indicate the increased complexity of the system.

The switch, S_1 or S_2, can fail in either of two ways. Considering S_1:

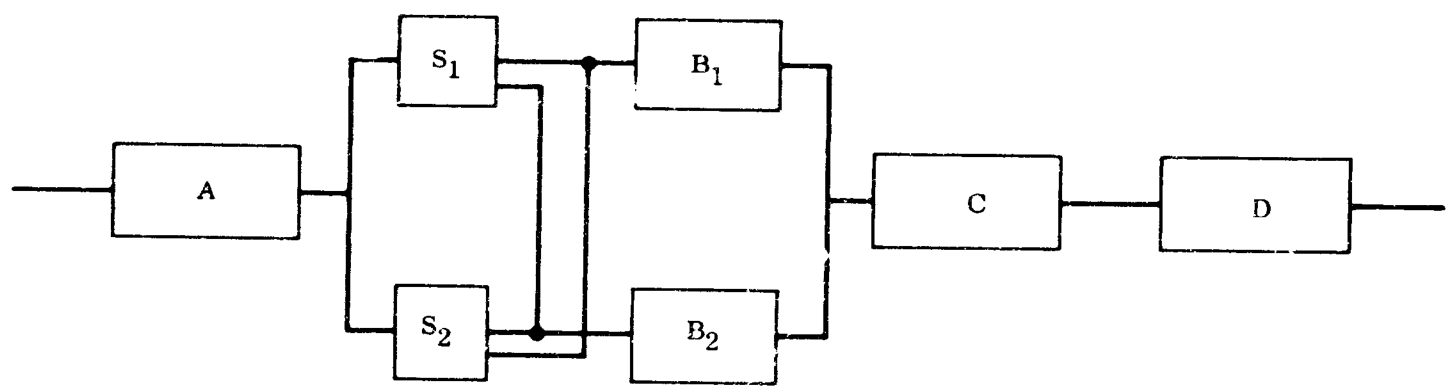
(1) It can fail to cause a transfer from B_1 to B_2 when B_1 fails;

(2) It can, in error, cause a transfer to B_2 when B_1 has not failed.

Let's take a closer look at that switch. It might be a starting valve for the diesel engine driving generator B_2, held in the closed position against spring pressure by a solenoid energized whenever there is a voltage output from B_1. The valve is, of course, locked closed electrically whenever the generator it starts is running. Failure by the first mode might be a mechanical failure, such as the valve freezing shut or a mechanical linkage broken. Should this type of failure have occurred, the valve cannot operate on a failure of B_1, hence a failure of B_1 would cause the entire system to fail. Failure of the switch by mode 2 might be an electrical failure, an opening of the coil permitting the valve to open, starting generator B_2 and connecting it to the line. An interlock is presumably provided to shut down the diesel engine driving generator B_1, disconnecting the generator from the line, where it remains ready to start again should generator B_2 fail. Should the switch fail in the second mode, the operation is still successful unless the generator B_2 fails. If this should occur, the identical switching arrangement on generator B_2 cannot successfully transfer back to B_1 since each attempt to transfer back will result in the switch failure trying to start B_2 and dropping B_1 off the line.

Looking at just the four equipments (B_1, B_2, S_1 and S_2) we can identify the possible events that may occur. To describe the possible outcomes an abbreviated notation will be used.

STANDBY PARALLEL CASE



B_1 Means generator B_1 operates successfully.

$\overline{B_1}$ Means generator B_1 fails.

SM_1 Means switch S_1 operates successfully to transfer from B_1 to B_2.

SE_1 Means switch S_1 does not fail electrically and so does not cause an unnecessary transfer from B_1 to B_2.

$\overline{SM_1}$ Means switch S_1 fails to activate to cause a transfer to B_2 on the failure of B_1.

$\overline{SE_1}$ Means switch S_1 transfers the load to B_2 while B_1 is still operating correctly.

The same notation will be used referring to the performance of generator B_2 and switch S_2. (Figure 4-38). Note that the bar above the abbreviation denotes unsuccessful operation.

The probability that at least one of the eight indicated sequences occurs is 1.0. The sum of the probabilities of all possible sequences, then must add up to 1.0. To compute the reliability, or probability of success, we can compute the individual probabilities that each successful sequence occurs and add them, or we can compute the probability that each unsuccessful sequence occurs and subtract the sum from 1.

Successful Sequence 1 can be seen to be: B_1 operates successfully, S_1 does not fail electrically.

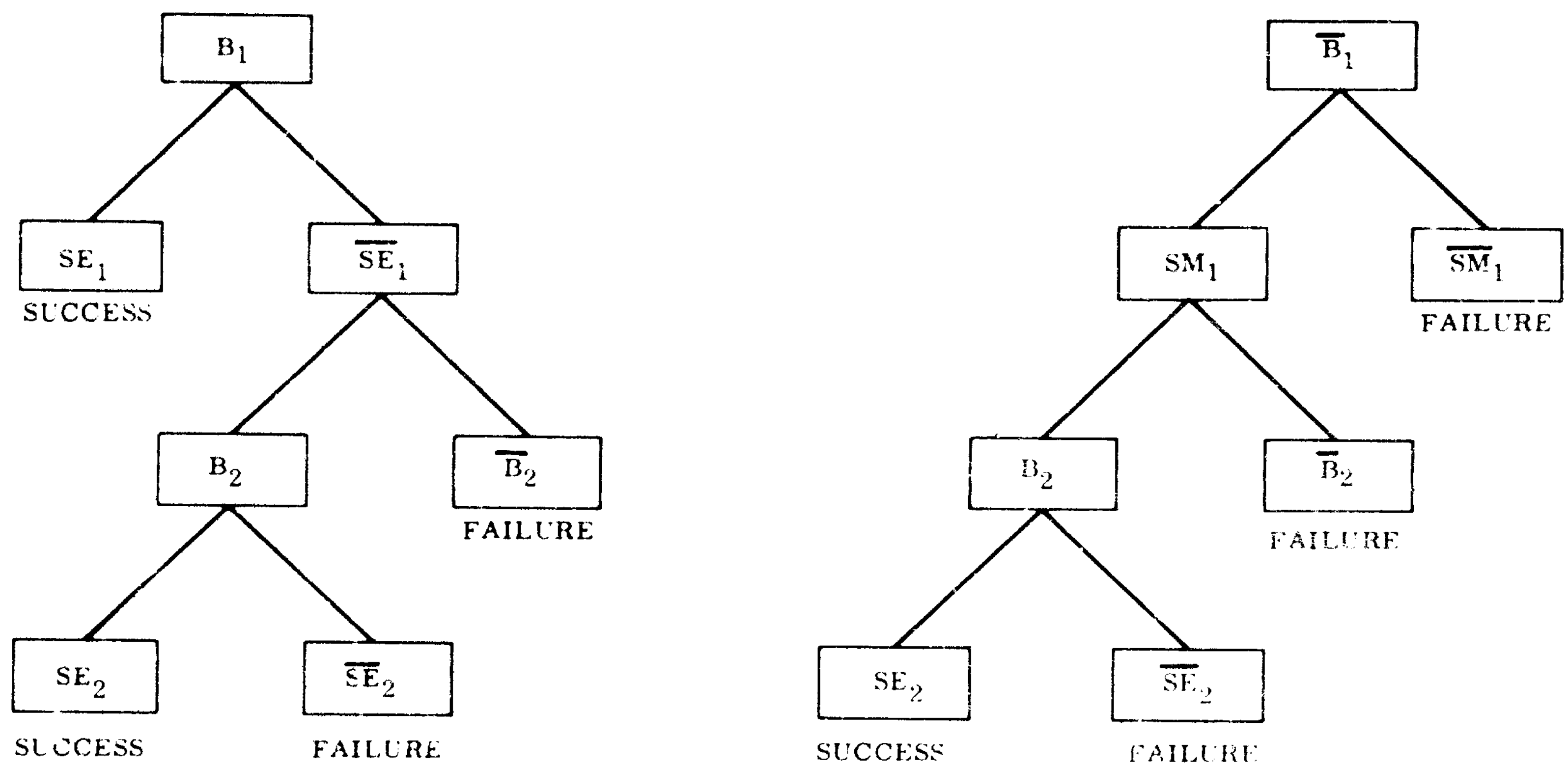
Successful Sequence 2 is seen to be: B_1 operates successfully but Switch S_1 fails electrically, transferring the load to B_2. B_2 operates successfully and S_2 does not fail electrically.

Successful Sequence 3 can be seen to be: B_1 fails, Switch S_1 operates mechanically starting generator B_2. B_2 operates successfully with no electrical failure of S_2.

Consider now the question. What is the probability that either B_1 or B_2 will operate successfully for a time t.

$$R\ (\text{Sequence 1}) = R_{B_1} \times R_{SE_1} = e^{-(\lambda_{B_1} + \lambda_{SE_1})t}$$

POSSIBLE SEQUENCES



$$R \text{ (Sequence 2)} = R_{B_1} \times R_{B_2} \times R_{SE_2} \times (1 - R_{SE_1})$$

$$= e^{-\lambda_{B_1} t} \times e^{-(\lambda_{B_2} + \lambda_{SE_2})\frac{t}{2}} (1 - e^{-\lambda_{SE_1} t})$$

$$R \text{ (Sequence 3)} = R_{SM_1} \times R_{B_2} \times R_{SE_2} \times (1 - R_{B_1})$$

$$= e^{-(\lambda_{SM_1} + \lambda_{B_2} \times \lambda_{SE_2})(\frac{t}{2})} (1 - e^{-\lambda_{B_1} t})$$

Although this is not capable of reduction to a form $R = e^{-\lambda t}$, it can be solved to provide a numerical answer R_{BS}. This answer can then be multiplied with the combined product R_{ACD} to obtain the final answer.

Assuming a negative exponential distribution of times to failure for the various components as in the previous example, with reliabilities of the switches as follows:

	MTBF	λ
SE1, SE2	50	.020
SM1, SM2	75	.013

The probability of the successful sequences can be computed to be

1) .905 x .961 = .870

2) .905 x .039 x .935 x .980 = .032

3) .095 x .987 x .935 x .980 = .086

The probability of successful operation for a two hour period can be seen to be the sum of the probabilities or .988.

The probability of successful operation of the system is .988 x .781 = .763

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Chapter 5

RELIABILITY PREDICTION

Chapter 5

RELIABILITY PREDICTION

Reliability prediction, performed as part of the system development, is analogous to the analyses the designer makes on measurable performance characteristics such as voltage, pressure or temperature. In design, the designer computes the expected performance values. He used techniques verified by previous experience. Later testing merely confirms his analysis. While reliability is not measurable in the same sense, it is a tangible characteristic of the design. Reliability prediction is the analytical method of determining what the consequences of design decisions made before the manufacture and test of the equipment will be. It is based on techniques confirmed by previous experience. It provides a quantitative measure of the reliability of the equipment as designed which may be compared to the requirements to assure that the final design has achieved those requirements. The operational reliability of the equipment may be compared against the predicted value to identify areas where improved training or improved production processes can be effectively used. In this chapter we will describe how the prediction is performed.

As described in Chapter 3, the prerequisite for performing a system analysis is a description of the system. This description is usefully provided by a system model, including

(a) Identification of the system to its component parts.

(b) Definition of failure of the system in terms of functions required.

(c) Environment in which the system must operate.

(d) Time of required operation.

For reliability prediction, the system model must describe the relationship between component failures and system failures. This relationship for most systems can be adequately represented by either series (serial) or parallel (redundant) models or by combinations of the two as discussed in Chapter 4. In the series system it is assumed that a failure of any of the components will result in the failure of the system, or in other words, the system will operate successfully only if all the components operate successfully. This is analogous to a series electrical lighting circuit. In a parallel system, it is assumed that the system will fail only if all the components fail, or in other words, the system will operate successfully if any one of the components operate successfully. This is analogous to a parallel electrical lighting circuit.

As a quick review, the system models can be more precisely described in terms of events, the success or failure of the components of the system. Let S denote the event that the system is successful and S_j the event that the j^{th} component operates successfully. The event S in a series system made up of m components can be expressed as a combination of the events S_j, j=1, 2,...,m, as

$$S = S_1 \text{ and } S_2 \text{ and} \ldots \text{and } S_m$$

the intersection of the events S_j. In a similar way, the event S in a parallel system can be expressed as a combination of the events S_j.

$$S = S_1 \text{ or } S_2 \text{ or} \ldots \text{or } S_n$$

the union of the S_j.

The reliability of the series system can then be written

$$R = P(S) = \prod_{j=1}^{n} P(S_j) = \prod_{j=1}^{n} R_j$$

in which R_j is the reliability of the j^{th} component. In the same manner, the reliability of the parallel system becomes

$$R = P(S) = 1 - \prod_{j=1}^{m} (1-P(S_j)) = 1 - \prod_{j=1}^{m} (1-R_j)$$

Techniques useful in the analysis and prediction of equipment reliability have been under development since about 1957. In the field of electronics the techniques have been developed extensively; the methods utilized in evaluating reliability in mechanical systems has been a more recent development. At the same time that the prediction techniques have been evolving, emphasis has been placed on the gathering of failure-rate data on parts and the measurement of reliability of existing equipments in order to provide numerical significance to the various mathematical expressions used in describing reliability. <u>It must be remembered that the real value of these numerical expressions lie not in the number itself, but in the information it conveys and the use made of that information.</u> Reliability predictions do not, in themselves, contribute to the reliability of a system. Control of failure frequency for any system can be improved with more complete knowledge of failure modes and failure mechanisms (Chapter 12). Reliability predictions provide a set of criteria for selecting courses of action for this investigation and, therefore, affect the actual reliability of a system.

Reliability prediction techniques are those methods used to obtain a numerical indication of the inherent reliability of a device. Inherent reliability is the reliability potential of the design, excluding the degradation which will occur in production, storage and operational use.

1. STAGES OF DESIGN vs PREDICTION

Reliability predictions should be started as soon as the design begins to take shape in identifiable components, before the selection of such components as parts of the system is made. The prediction should be used as a working design tool, used to compare the effect of alternate possible courses of action so that the best can be selected. The prediction should be kept current as the design becomes more fixed, to be used in evaluation of interface problems, to confirm previous analyses as test results accrue and to provide an analytical evaluation for proposed changes. The prediction changes as the design develops as follows:

1.1 PRE-DESIGN

Predictions made in the pre-design stage are based on little or no detailed design information. They are used in feasibility studies, evaluation and comparison of alternate design configurations, and in reliability allocation. Because of the limited information on which they are based, these predictions cannot be as precise as later predictions. These initial (pre-design) predictions do not contribute appreciably to identifying specific reliability problems or indicating areas of data deficiency. However, by influencing decisions on design concepts and the scope of the reliability program, they can have a substantial influence on system reliability and system development.

1.2 DESIGN

Pre-design predictions must be updated periodically in order to aid in making timely decisions on design details as well as on the other elements of the program. Predictions during the design phase are made after the pre-design prediction and prior to design completion. As the design progresses, consecutive predictions can be made with increasing precision. These successive predictions will be based on the accumulated knowledge of the parts to be used, the application stresses, the manner in which the functions are accomplished, and the environmental conditions to which the parts will be subjected.

1.3 COMPLETED DESIGN

When a design is completed, an updated prediction is made. This prediction will be the best reliability estimate, before actual reliability measurement through operational testing, because it will reflect complete design information. This is not the final prediction to be made on this design, however. As the design is changed the reliability prediction must be revised accordingly.

2. RELIABILITY PREDICTION APPROACH

2.1 TYPES OF FAILURE

A system is a collection of parts mechanically and/or electrically joined together in order to perform certain specified functions. If a system is capable of satisfactorily performing its functions at some point of time, it will continue to have that capability until a significant change occurs in the operating characteristics of some part, or group of parts. Part failure occurs when the characteristics of a part, or group of parts, have changed to the point where they exceed the limits within which the system functions are satisfactorily performed. Whenever a system fails, a group of parts have failed. Thus, the reliability of a system is directly related to the number of parts it contains and the reliabilities of these individual parts.

The prediction of the reliability of a system is the determination of the expected reliabilities of individual parts as they are used in the system. The reliability of a part is determined by three factors: (a) characteristics of the part at the beginning of the operating period of interest, (b) the characteristic limits which constitute failure, and (c) the magnitude of the changes occurring in characteristics during the period of operation, which may be directly related to environment, or physical or electrical stress.

We consider two categories of parts failure. The first (Catastrophic Failure) is that in which functional characteristics change abruptly and drastically, e.g., a tube becoming inoperative due to heater opening or a pump bearing seizure. The second category (Drift Failure) is that in which there is a relatively gradual change in measurable functional characteristics until operation is no longer satisfactory, e.g., a tube whose transconductance diminishes to the point of failure due to a build-up of interface resistance, or the gradual wear on the pivot of a cam, permitting a misalignment in an operating mechanism.

Prediction of failure is a process that remains basically the same regardless of the data or procedures used. It is based on the premise that like parts have approximately the same reliability in one system as in any other system, if they are subjected to the same stresses. This permits the application of data obtained from prior operation of parts to predict their reliabilities in new systems.

At this point we must further clarify the relationship between part failure and system failure. A part used in a redundant element of a system cannot cause the system to fail unless the other redundant element "fails." For parts in a redundant element, failure is redefined as occurring when the characteristics of a part, or group of parts, exceed the limits within which the system's functions would be satisfactorily performed if the part(s) were not in a redundant path. Therefore, the reliability of a system which contains redundant elements is not simply the product of the reliabilities of its parts. A more complete formula relating system reliability to part reliabilities must be used for predicting the reliability of a system which includes redundancy (see Chapter 4).

2.2 VALIDITY OF THE EXPONENTIAL DISTRIBUTION

The assumption of the exponential distribution of times to failures in conducting predictions of reliability of systems is usually made because of three facts.

(a) In general, sufficient data is not available to provide confidence in the selection of an alternate distribution.

(b) The mathematical computation is greatly simplified by this assumption.

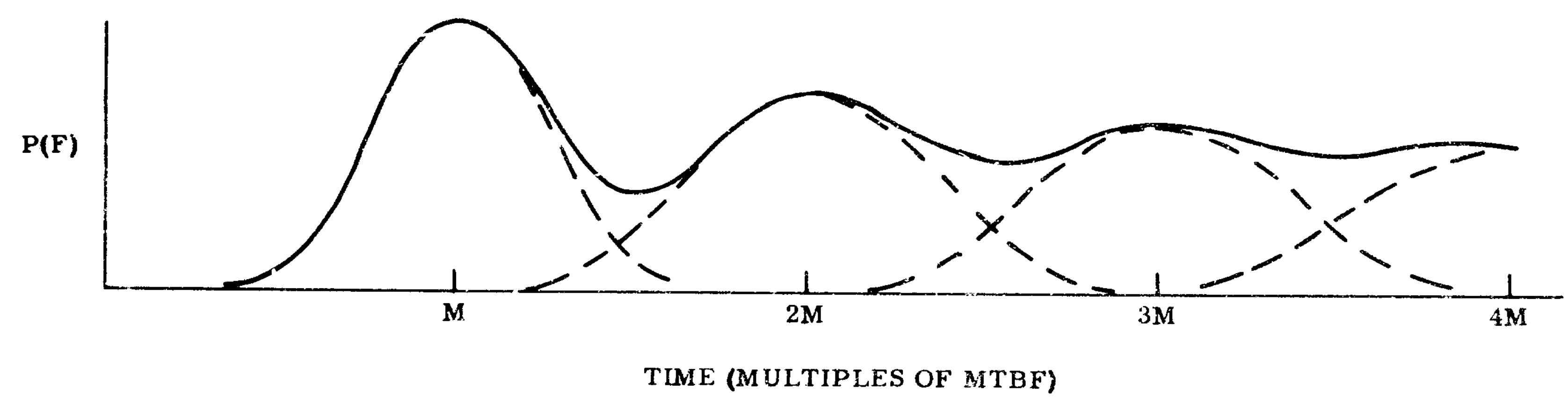
(c) It provides answers on the conservative side.

Lacking any theoretical basis for assigning a distribution of time to failure, one naturally turns to empirical data for possible generalizations about the nature of the distribution. In 1952, Davis (3) published an article containing an analysis of failure data from a wide assortment of unrelated systems. He concluded, "The exponential theory of failure appears to describe most of the systems examined here. Those systems which exhibit reasonable agreement with this failure theory are characterized by predominance of human errors as the cause or a careful and well developed operating technique for minimizing failure. Systems which are subject to a wide range of environmental severity also appear to follow this pattern." He also found that some of the systems examined generated failures in a way best described by a normal distribution, but these systems were characterized by what we now refer to as wearout failures.

The Davis article has been referred to quite often as justification for the assumption of an exponential distribution of the time to failure of electron tubes. Further evidence was published in a series of ARINC monographs (4, 5, 6, 7), in which a large number of electron tube failures were found to follow an exponential distribution. Other electronic components, however, were found to fail in a manner best described by a normal distribution. Kao (7) has more recently found that a Weibull distribution best fitted the failure data relative to over two thousand electronic tube failures. Weaver and Smith (8) have found that the failure times of certain electromechanical devices can best be fitted by a mixed Weibull distribution. The above evidence casts doubt on the notion that a single distribution can safely be used to represent all types of failures.

MacFarlane and Mickel (9) show that the exponential time to failure assumption provides a reasonably accurate solution in the case of normally distributed times to failures where each failure is repaired as it fails, as long as the standard deviation is greater than one tenth of the mean life of the parts. The important concept is (Figure 5-8) that when a population of life parts enter service together at time t = o, they will all fail in a greater or less concentrated period centering about their mean life. When, however, each of the part population has been replaced several times, thereby maintaining the population, the individual ages of the replacements become so well mixed that failures and renewals occur in nearly random fashion. As the equipment becomes more complex and as parts each portraying individual failure characteristics increase in number, the "Random" approximation improves in accuracy.

RATE OF FAILURE AND RENEWAL



The best procedure to follow in selecting the distribution to use in the computation is to examine whatever evidence might be at hand, select a distribution which seems to be compatible with the evidence, and submit the selected distribution to suitable statistical tests of goodness of fit. For example, if it seemed reasonable to the engineer that a constant failure rate would be a characteristic of the device, one may hypothesize that the time to failure follows an exponential distribution. If wear out failures are expected, a normal distribution may be a suitable first estimate. Experience with similar devices may indicate that a Weibull distribution is appropriate. In the absence of any technical reasons for selecting a particular distribution, one might examine several of the distributions which may be compatible with the expected failure pattern. The Weibull, exponential, normal, and gamma distributions would all be suitable candidates for a first approximation. Distributions of time to failure are carried to greater depth in Chapter 9.

For the purposes of prediction of reliability, in the absence of good information on the distribution of times to failure, the assumption of the negative exponential distribution should be used.

2.3 RELIABILITY PREDICTION APPROACH

To accomplish the prediction of reliability of a complex system, the following steps are recommended.

(a) Develop the system model (Chapter 3)

(1) Mission Objectives and Requirements
(2) Functional Flow Diagram
(3) Event Sequencing and Operating Times
(4) System Operation Modes
(5) Environmental Profile
(6) Success/Failure Criteria
(7) Logic Representation

(b) Develop a formula for the combination of individual failure rates (or mean times between failures) of the subsystems or components to derive the reliability of the system (Chapter 4).

(c) Compile parts lists for subsystems or components.

(d) Perform Stress Analysis.

(e) Assign failure rates to parts.

(f) Combine part failure rates to determine reliabilities of subsystems or components.

(g) Compute system reliability.

2.4 COMPILATION OF PARTS LISTS

List the individual parts comprising each block of the reliability block diagram. Even though all parts of block are listed only those parts which can cause the failure of a block are considered in the reliability prediction. Parts lists will serve as basic worksheets to determine stresses, part failure rates, and estimates. When entering part descriptions, also record ratings, operating voltages, currents and power dissipation.

2.5 STRESS ANALYSIS

Record on the worksheet the operating voltages, currents and other characteristics needed to calculate stress levels of electronic equipment (for mechanical equipment, a limited amount of data is available correlating the rate of failure with stress levels).

(a) Determine from design analysis and/or actual measurements the operating voltages, currents, power dissipation, etc., for each part.

(b) Calculate the stress levels by comparing operating characteristics or conditions with the rated values.

2.6 ASSIGNMENT OF PART FAILURE RATES OR PROBABILITIES OF SURVIVAL

This step in the reliability prediction consists of assigning failure rates, or some other measure of reliability, to the individual parts. Most part failure rate data is computed assuming a negative exponential distribution. The stress levels, determined in the stress analysis, ambient temperatures, and other applicable information will be used to modify or adjust these failure rates for use in a particular system and/or application. If the stress levels or the environmental characteristics vary during a mission, separate failure rates must be calculated for each mission phase.

It is evident that a key factor in making a reliability prediction is the determination and/or availability of failure rates. In some cases the failure rate of an equivalent equipment can be obtained directly from past performance data. However, the failure rate of an equipment is not generally available in the design stage. This is due to the lack of operating and failure data from which a failure rate could be determined. Therefore, the determination of the failure rate of an equipment while in the design stage is usually based on the details of the design that are known, i.e., types of parts, ratings, type, duration and magnitude of stresses expected, and the kind of operating and failure data from which the expected failure rate can be determined.

2.6.1 Sources of Part Failure-Rate Data:

A. Shipboard Applications

1. Handbook for the Prediction of Shipboard and Shore Electronic Reliability by R. G. Stokes (NAVSHIPS 93820, Apr. 1961).

2. A Summary of Reliability Prediction and Measurement Guidelines for Shipboard Electronic Equipment (Vitro Labs Rpt. #98, Apr. 1957).

3. Techniques for Reliability Measurement and Prediction Based on Field Failure Data (Vitro Labs Rpt. #80, Oct. 1955).

4. Study of Maintenance Cost Optimization and Reliability of Shipboard Machinery (United Control Corporation Report, June 1962). (AD283428.)

B. As a Function of Electrical & Environmental (External) Stress

1. Reliability Stress Analysis for Electronic Equipment (RCA Rpt. #TR-1100 or NAVSHIPS 900-193, Nov. 1956). (RCA Report TR59-416-1 updates this.)

2. Philosophy and Guidelines for Reliability Prediction of Ground Electronic Equipments (RCA Rpt. #R4-57, Oct. 1957).

3. Reliability: Predicting Thermal Results by

T. C. Reeves (Military Electronics, July 1957).

4. RADC Reliability Notebook (Report #RADC-TR-58-111).

5. Reliability Stress Analysis for Electronic Equipments, MIL-HDBK-217, 31 Dec. 1961.

6. Prediction of Field Reliability for Airborne Electronic Systems, ARINC Research Corporation Publication No. 203-1-344, 31 Dec. 1962.

C. Utilizing Adjustment (K) Factors

1. Investigation of Electronic Equipment Reliability (Aeronautical Radio, Inc., Air Force Reliability Assurance Program, Progress Rpt. #1, Feb. 1956).

2. Improved Techniques for Design-State Prediction by H. B. Brown, W. C. Fredrick, and H. J. Kennedy (Air Force Reliability Assurance Program, Progress Report #2, ARINC Research Corp., Pub. #110-1-136, Apr. 1959).

3. Reliability and Maintainability of Military Electronic Equipment by J. H. Hershey (Bell Telephone Labs, 3rd Signal Maintenance Symposium, Apr. 1959).

4. Reliability Analysis for Electronic Equipment, Radio Corporation of America, TR-59-416-1, Jan. 1959.

5. "Component Part Failure Rate Analysis for Prediction of Equipment Mean Life," R. L. Vander Hamm, Collins Radio Co., CTR 195, March 1958.

6. "Reliability Evaluation Techniques for Electronic Equipment," Defense Electronic Products Division, Radio Corporation of America, Central Engineering, Camden, N. J., Vol. 14, 1962.

D. Generic Failure Rates & Application (K) Factors

1. Component Part Failure Rates Associated with Installation Environment by D. E. Earles (Martin-Denver Report #M60-47, Dec. 1960).

2. Reliability Growth Prediction During the Initial Design Analysis by D. R. Earles (Proceedings of the 7th National Symposium on Reliability and Quality Control, January 1961).

3. Reliability Application and Analysis Guide by D. R. Earles (Martin-Denver Report #M60-54, Failure Rate Handbook, July 1961).

4. Bureau of Naval Weapons Failure Rate Data Handbook, (FARADA). U.S. Naval Ordnance Lab., Corona, California. (Available only to qualified contractors and government agencies.)

5. Failure Rates, D. R. Earles and M. F. Eddins, AVCO Corporation, April 1962. (An updated version appears in Proceedings, Ninth National Symposium on Reliability and Quality Control, Jan. 1963.)

6. Temco Reliability Manual - Vol. I, C. M. Schwalm, Temco Electronics and Missiles Company, Dallas, Texas, July 1961.

E. Mechanical and Electro-Mechanical Devices

1. Proposed Procedures for Reliability Stress Analysis of Mechanical and Electro-Mechanical Devices by I. Kirkpatrick (RCA, Ltd., Report #176, Feb. 1958).

2. Reliability Analysis Data for Systems and Component Design Engineers, General Electric Company, Missile and Space Vehicle Department, Report TRA-873-74, distributed by U. S. Department of Commerce, Office of Technical Services, Washington 25, D. C., as PB 181080.

F. Assigning Reliability Indices

1. Prediction of Missile Reliability by H. R.

Powell and M. J. Kirby (Sperry Engineering Review, Jul.-Aug. 1955).

G. Active Elements

1. One Reliability Prediction in Satellite Systems by G. T. Bird (ARINC Research Corp. Pub. #4226-1-205, May 1960).

2. A Technique for Estimating Ballpark Reliability Figures by Tube Counting (RADC Rpt. #RADC-TN-58-81, March 1958).

H. Part Variability

1. Designing Reliability into Electronic Circuits by A. H. Benner and B. Meredith (Proceedings of the National Electronics Conference, Vol. 10, 1954).

2. Circuit Design Concepts for High Reliability by F. E. Dreste (Proceedings of the 6th National Symposium on Reliability and Quality Control, 1960).

3. Statistics: Key to Reliable Military Electronic Design by F. E. Dreste (Military Electronics, Vol. VI, No. 3, March 1959).

4. The Evaluation and Prediction of Circuit Performance by Statistical Techniques by S. Marini and R. T. Williams (Proceedings of the Joint Military-Industry Guided Missile Reliability Symposium, Nov. 1957).

5. Designing for Reliability by S. A. Meltzer (IRE Transactions on Reliability and Quality Control, Sept. 1956).

6. Reliability and Components Handbook (Motorola Western Military Electronics Center, Jan. 1959).

7. Electronic Parts Failure Rates Analysis by D. J. Fisk, Hughes Aircraft Company, Aerospace Group, Culver City, California, Feb. 1963.

8. Reliability Data Book - Engineering Reliability,

Martin Company, Electronic Systems and Products Division, Baltimore, Maryland, June 1962.

These sources contain part failure rates based on part characteristics and applied stresses. The same source of failure rates should be used throughout all reliability prediction calculations (for a particular system) because the failure rate for the same part may be different in each of the sources. This is due to the fact that the failure rates in each source are not based on the same operating conditions and/or failure criteria. These sources categorize parts and tubes by their physical characteristics and function. Variations in failure rates are presented as a function of stress severity expected and the stress level for which the part is rated, i.e., voltage, power, frequency, temperature, actuation rate, speed of rotation, etc.

2.6.2 Failure Rates: Failure rates can be expressed in various ways:

(a) Failures per hour

(b) Percent failures per thousand hours

(c) Failures per thousand hours

(d) Failures per million hours

(e) Bits

The bit is usually considered to be the minimum failure rate which would be experienced and is equal to 1×10^{-8} failures per hour.

Table 1 is provided as an aid in converting failure rates to the desired units. To use the table, select the units to be converted at the left and multiply by the factor at the intersection with the column headed by the desired units, e.g., to convert a failure rate of 1.4% failures per thousand hours to failures per hour, multiply 1.4 by 10^{-5} to obtain 0.000014 failures per hour.

TABLE [illegible]

CONVERSION UNITS FOR FAILURE RATES

	Bits	Fails/10^6hrs	%/10^3hrs	Fails/10^3hrs	Fails/hr
Bits	1	10^{-2}	10^{-3}	10^{-5}	10^{-8}
Fails/10^6 hrs	10^2	1	10^{-1}	10^{-3}	10^{-6}
%/10^3 hrs	10^3	10	1	10^{-2}	10^{-5}
Fails/10^3 hrs	10^5	10^3	10^2	1	10^{-3}
Fails/hr	10^8	10^6	10^5	10^3	1

2.6.3 Environmental Stress Correction: The availability of dependable failure rate data is essential in order to arrive at a meaningful reliability prediction. Unfortunately, the data available from the various sources are based on dissimilar failure criteria and/or different use environments. It is for this reason that the tabulated failure rates may vary considerably. A list of a few basic failure rates from thirteen sources is presented in Figure 5-17. An inspection of the table shows that it is not uncommon to have variations of three orders of magnitude for many types of parts.

For example, the data presented in MIL-HDBK-217 are based on three classes of ground-based equipments; i.e., a long-range search radar, a communications radio set, and a radar identification set. Part failure rates are considered to apply to ground based or laboratory bench conditions. In comparison the data presented in NavShips 93820 was based on average severity levels found to represent several dozens of equipment types used in shipboard applications. ARINC Research Report 203-1-344 was based on some 200 million hours of operation in 9 different airborne systems.

It is evident that care must be followed in selecting and utilizing any source of failure rate data for a specific system and/or application. There are wide variations in the quality of failure and data analysis as well as the effects of factors such as success/failure criteria, applied stresses, and operating environments. Many types of parts do not have derating curves available. The FARADA Handbook offers by far the widest selection of data, with good source documentation. Care must be taken

PART FAILURE RATE COMPARISONS

Failures Per Million Hours

	ARINC (1)	COLLINS (2)	BOEING (3)	AUTONETICS (4)	(5)	G.E. (6)	PHILCO (7)	STL (8)	RCA (9)	RCA (10)	IBM (11)	BTL (12)	RCA (13)
CAPACITORS													
Ceramic		0.49				0.2		0.01	0.57	0.35	0.1		0.35
Electrolytic		2.34									0.6		2.92
Mica		0.43	1.0			0.1		0.01	0.46	0.15	0.1		0.01
Paper		0.94	5.0					0.01	0.50	0.17	0.6		0.17
CONNECTOR	1.5	0.7		10.0	2.0	0.5	2.0		0.06	2.0	0.1	0.01	0.3/Pin
QUARTZ CRYSTAL				10.0	2.0				1.36		36.2		0.2
DIODES	17.2	4.5		0.3	0.3	3.5							
Germanium							0.3			8.6		0.3	0.54
Selenium	50.0									7.15	6.0		
Silicon	120.0		3.0					0.15		3.85	172.0	0.2	0.5
MOTOR, AC	88.0	23.0	556.0	10.0	5.0		10.0	0.50		11.5	15.0	0.15	16.0
MOTOR (SYNCHRO)	45.0		200.0	50.0	20.0				1.80	11.5	18.0		10.0
SWITCH	25.0	7.0	33.0	20.0	5.0		0.4	0.3	.48	1.5	10.0	0.03	0.58
TRANSFORMER	16.[illegible]	4.0				10.0		0.2	1.16	1.5	1.9		5.0
TRANSISTOR	17.3	10.0	14.0	10.0	1.0	5.0-	0.1		1.03				9.0
Germanium											2.0	0.9	0.76

FAILURE RATE DATA SOURCES

1. ARINC AFRAP Report
   Capacitors @ 50% Voltage
   Resistors @ 50% Rating
   Vacuum Tubes @ Class 4

2. Collins CTR 195, No Tradeoff Figure

3. BAC DOC D6-2770- No Tradeoff

4. Autonetics Bulletin 41 - No Tradeoff
   Commercial Grade Parts

5. Autonetics Bulletin 41 - No Tradeoff
   Autonetics Controlled Parts

6. G. E. Heavy Military Electronic Dept.
   No Tradeoff. 5th R & Q.C. Symposium

7. Philco Observed Rates - Transac S-2000 Computer

8. STL Rates used for "STEER"
   DTL Rates taken at 25% Rating, 30° C

9. VITRO TR-133 (NAVSHIPS 93820)

10. RCA TR-1100 (Old Edition)
    All Components @ 50% Rating, 40° C

11. IBM Extrapolated Failure Rates
    for Airborne Equipment

12. BTL Rates for Lab. Equipment, All Parts
    Operated at < 25% of Rating in 15-25° C
    Environment. Rates to be multiplied by
    Following Factors for Military Field
    use.

Use	Vacuum Tube Equipment	Transistorized Equipment
Lab.	1.0	1.0
MIL Ground Station	1.1	1.1
Ship	10.0	7.7
Trailer	20.0	14.3
Aircraft	33.3	25.0
Missile	83.3	62.5

13. RCA TR-59416-1
    All Components @ 50% Rating, 40° C

when using FARADA to convert failure rates to a common environmental base.

In many reliability prediction procedures the basic part failure rates must be modified to take into account the expected environmental, electrical, mechanical, and thermal stresses. A reasonable point estimate of system reliability can only be made after extensive stress analysis. The predicted reliability may not be as accurate as is desired, but the procedure is useful in focusing attention on potential areas of unreliability.

In general, correction factors will take a form similar to the following equation:

$$\lambda_a = \lambda_o (K_1 K_2 K_3 \ldots K_i \ldots K_n),$$

where λ_a is the adjusted failure rate, λ_o is the basic, or generic failure rate, and K_i represents the correction factors needed to modify the basic failure rate due to differences in applied stresses, ratio of likely tolerance failures to random catastrophic failures, external environments, maintenance practices, complexity, observed cycling effects, etc.

Reliability prediction techniques vary in the degree of utilization or consideration of correction factors.

a. AVCO method (Report listed in paragraph 2.6.1 D3): In order to predict the failure rate of a system, the parts generic failure rates, which have been normalized to laboratory computer conditions, are multiplied by application or derating factors and then by factors which represent the installation environment.

b. MIL HDBK 217 method (Reliability Stress Analysis for Electronic Equipments): To obtain a failure rate prediction for a system by this method, the parts basic failure rates are modified by expected electrical and thermal factors and then further modified by a factor related to the environment in which the system is expected to operate.

The following table compares the environmental factors used in the AVCO method with those used in the MIL HDBK 217 method.

TABLE 2

Installation Environment		Environmental Correction Factors AVCO	MIL HDBK 217
Shipboard		15.0	1.0
Ground		8.0	1.0
Aircraft		50.0	6.5
Missiles		900.0	80.0
Satellite:	Launch Phase	900.0	80.0
	Boost Phase	800.0	80.0
	Orbit Phase	1.0	1.0

2.6.4 Special Cases: Data applicable to parts whose failure rates change with time, to one-shot devices and/or to parts whose probabilities of survival do not depend on time, should be recorded in the form of a probability. If the probability of survival is time-dependent, the corresponding value must be recorded for each of the time periods under investigation.

2.7 COMBINING PART FAILURE RATE TO OBTAIN SYSTEM OR COMPONENT RELIABILITY

In the Radar example of Chapter 3, an example of redundant use of controls, transmitters, receivers and indicators was shown. The logic diagram, at the bottom of the chart (Figure 3-19) shows the alternate paths that would constitute success, similar to the example in Chapter 4, (Figure 4-37). An alternate method of a mapping technique for solving problems of combined series-parallel probabilities is given in Reference 10. The logic diagram shown describes the rule of combination of probabilities for the combined system. For each component (controls, synchronizer, transmitter) the subassemblies must be identified and a block diagram constructed to show the interrelationships so that any redundant sections can be identified. It is not usually warranted to attempt to evaluate redundancies between parts, (transistors, capacitors or relays), since in the usual design, such redundancies will have a relatively insignificant effect on the system reliability. In some special cases, where such redundancy is employed as a reliability improvement technique to solve a specific problem, it can and should be computed.

The failure rate of a block which contains only parts in series having constant failure rates is the sum of the parts failure rates. To obtain the failure rate of a block containing redundant groups of parts, or parts which do not have constant failure rates, substitute the part failure rates or probabilities in the block reliability formula developed from the system model.

3. COMPONENT RELIABILITY PREDICTION

Figures 5-22 and 5-23 demonstrate the computation of reliability of a component. All parts are considered in series, that is, a failure of any part will cause a failure of the entire component. The failure rates of the individual parts, corrected for application stress and environmental factors are added together to obtain a failure rate which is converted to the MTBF shown.

NAVSHIPS 93820 provides a more comprehensive example of prediction of reliability. It establishes four levels of reliability prediction for electronic equipment based on the degree of knowledge of the system. Method D, the most comprehensive, applies derating (or load factors) to the parts based on application data.

As previously mentioned, the prediction of reliability of mechanical systems in lagging far behind the electronic systems. Some data on expected failure rates for mature (well developed) mechanical components is available in the literature. This must be used with caution, but can be used with engineering judgment. If a proposed hydraulic system, for example, is about the size and sees about the same load factors as the hydraulic components in an airplane, data from airplane experience (FARADA for example) can be used. Where the sizes are much greater and the loads less, the values given may be extremely pessimistic. In this case, personal experience and consultation with suppliers of hydraulic components typical of the proposed system will provide a better guide.

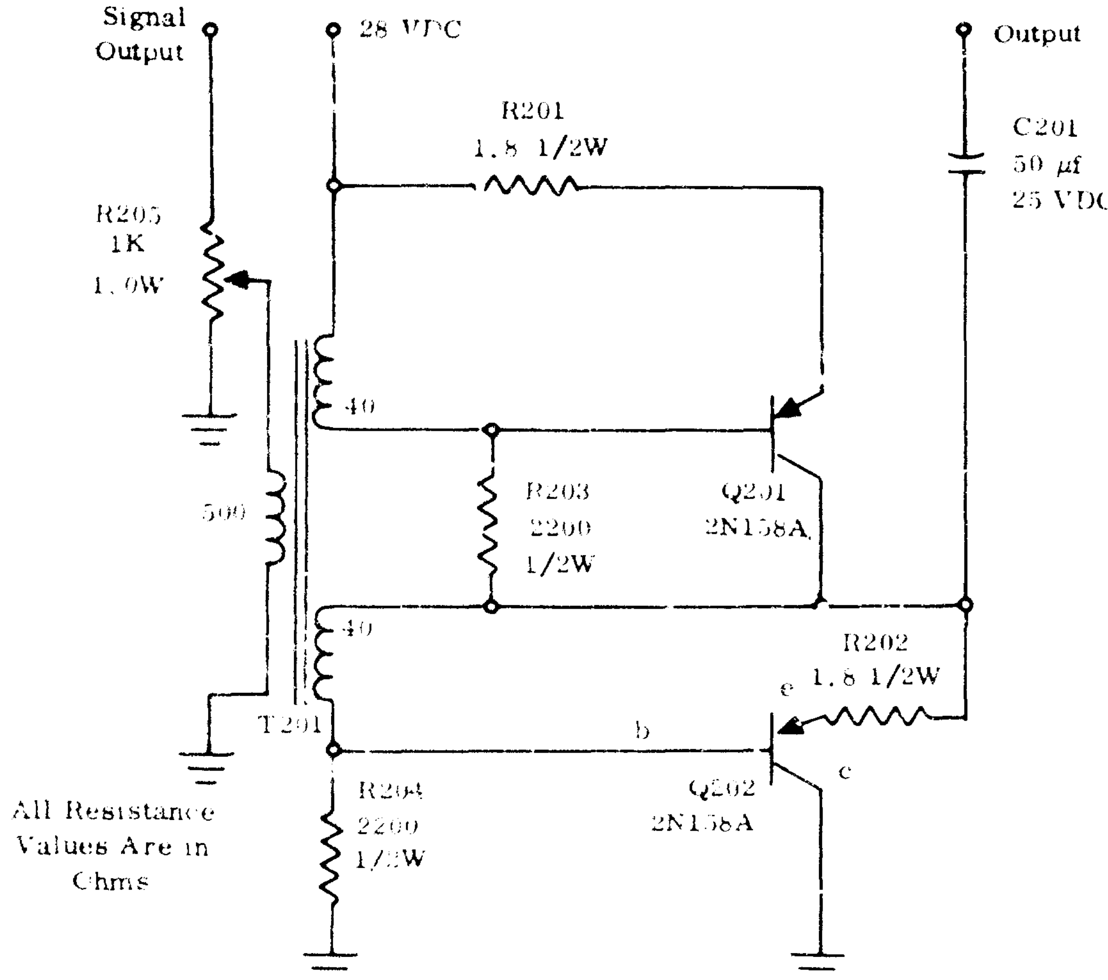
A prediction is an estimate of achievable reliability. Engineering judgment may in many instances be superior to available data. If the purpose of achieving high reliability is to be served, the engineer must seek out the facts and apply sound judgment to their interpretation. See Chapter 12 for a more comprehensive approach to the prediction of reliability of mechanical systems.

4. EXAMPLE OF SYSTEM RELIABILITY PREDICTION

4.1 TYPICAL SYSTEM

The first step in calculating the system reliability is to obtain a reliability estimate of the individual subsystems. The following reliabilities will be assumed for illustrative purposes (Figure 5-24):

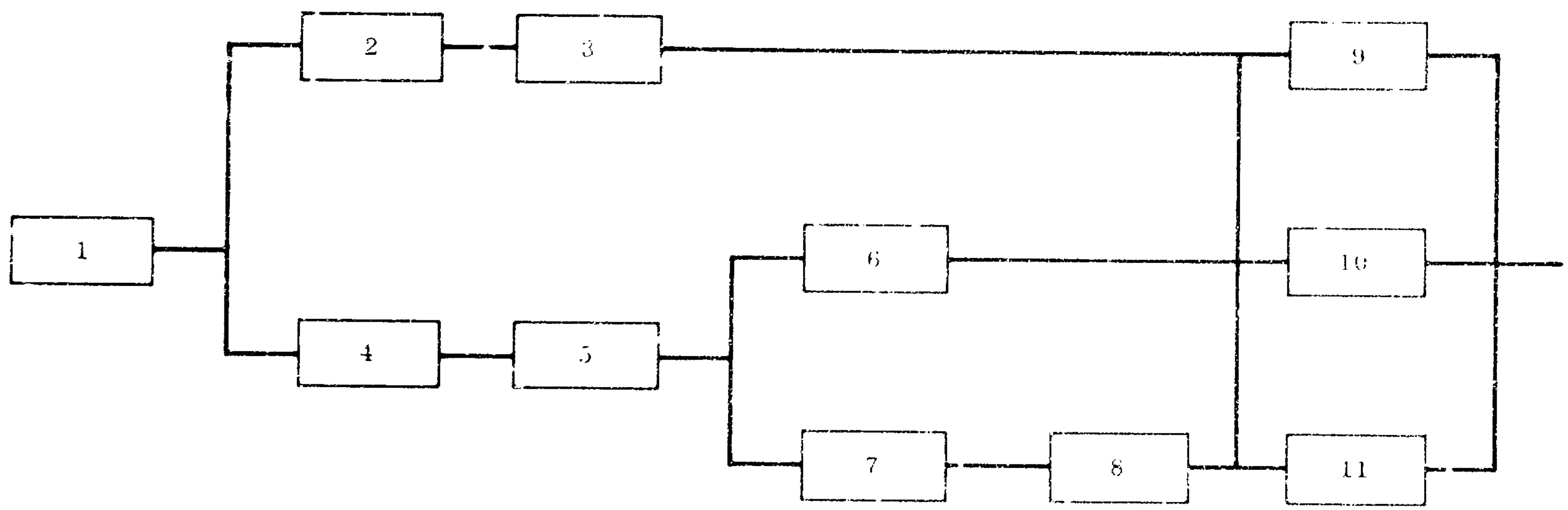
POWER AMPLIFIER



POWER AMPLIFIER RELIABILITY PREDICTION

Circuit Designation	Part Type	Applicable Specification	Operating Electrical Stress	Rated Electrical Stress	Stress Ratio	Ambient Temperature (°C)	Failures $/10^6$ Hours
Q 201	ZN158 A	MIL-T-19500A	2.12 watts	8.5 watts	0.24	40	1.03
Q 202	XN158 A	MIL-T-19500A	2.12 watts	8.5 watts	0.24	40	1.03
R 201	Fixed Wirewound	MIL-R-93	0.14 watts	0.5 watts	0.28	40	0.88
R 202	Fixed Wirewound	MIL-R-93	0.01 watts	0.5 watts	0.02	40	0.88
R 203	Fixed Composition	MIL-R-11B	0.11 watts	0.5 watts	0.21	40	0.26
R 204	Fixed Composition	MIL-R-11B	0.06 watts	0.5 watts	0.12	40	0.26
R 205	Variable Composition	MIL-R-94	0.01 watts	1.0 watts	0.01	40	0.44
C 201	Aluminum Electrolytic	MIL-C-62A		25 volts		40	1.83
T 201	Audio Transformer	MIL-T-27				40	1.25
TOTAL FAILURE RATE (λ) IN FAILURES $/10^6$ HOURS							7.86
TOTAL MTBF (T) IN HOURS							127,000

SYSTEM RELIABILITY BLOCK DIAGRAM



$R_1 = 0.9980$	$R_7 = 0.9980$
$R_2 = 0.9950$	$R_8 = 0.9989$
$R_3 = 0.9967$	$R_9 = 0.9983$
$R_4 = 0.9975$	$R_{10} = 0.9980$
$R_5 = 0.9987$	$R_{11} = 0.9967$
$R_6 = 0.9980$	

The next step is to reduce or combine the series and parallel circuits and establish successively simpler block diagrams. This is illustrated as follows:

Step 1: Reduce the parallel combination of items 9, 10, and 11 to single Item A, in series with the remaining circuit. (Figure 5-26)

$$R_A = 1 - (1 - R_9)(1 - R_{10})(1 - R_{11})$$

$$= 1 - (1 - 0.9983)(1 - 0.9980)(1 - 0.9967)$$

$$= 0.9999 +$$

Step 2: Reduce the series parallel combination of Items 6, 7, and 8 to a single Item μ.

$$R_\mu = 1 - (1 - R_6) \cdot (1 - R_7 R_8)$$

$$= 1 - (1 - 0.9980 [1 - (0.9980)(0.9989)]$$

$$= 0.9999 +$$

Step 3: Reduce the series combination of Items 2 and 3 to a single Item L.

$$R_L = R_2 \times R_3$$

$$= 0.9950 \times 0.9967$$

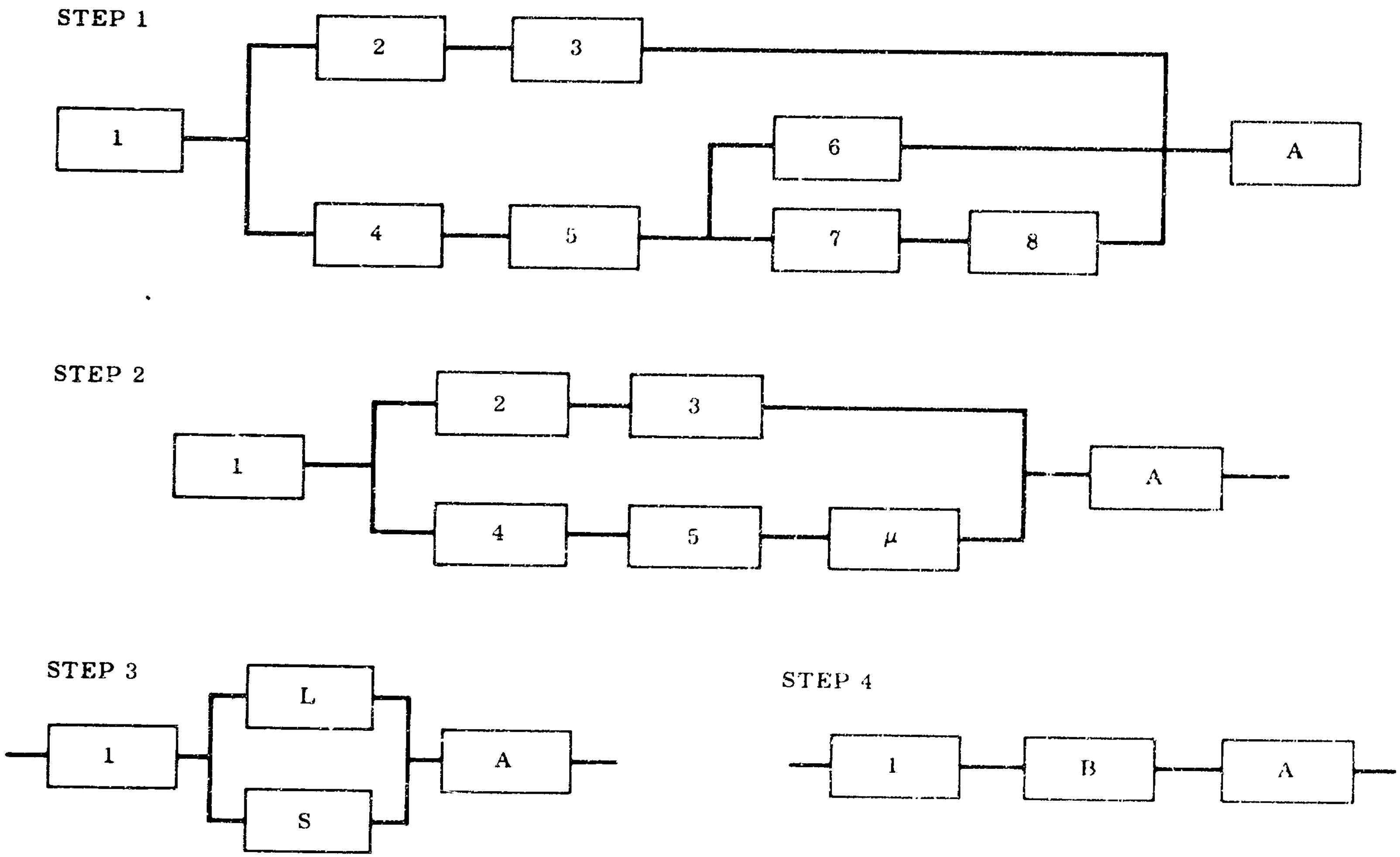
$$= 0.9917$$

Reduce the series combination of items 4, 5, and μ to a single Item S.

$$R_S = R_4 \times R_5 \times R_\mu$$

$$= 0.9975 \times 0.9987 \times 0.9999 +$$

SIMPLIFICATION OF DIAGRAM



$= 0.9961 +$

Step 4: Reduce the parallel combination of Items L and S to a single Item B.

$$R_B = 1 - (1 - R_L) \cdot (1 - R_S)$$

$$= 1 - (1 - 0.9917)\ (1 - 0.9961)$$

$$= 0.9999 +$$

Step 5: By reducing the series combination of Item 1, B, and A we get the overall system reliability, R_{total}.

$$R_{total} = R_1 \cdot R_B \cdot R_A$$

$$= 0.9980 \times 0.9999+ \times 0.9999+$$

$$= 0.9978 +$$

The reliability of a system composed of two parallel redundant branches, each containing two series subassemblies would be calculated from the following equation: (Figure 5-28).

$$R_S = 1 - (1 - R_{A_1}\ R_{B_1})\ (1 - R_{A_2}\ R_{B_2})$$

A system composed of two series sets of parallel redundant subassemblies would have a reliability given by the following equation:

$$R_S = [1 - (1 - R_{A1})\ (1 - R_{A2})][1 - (1 - R_{B1})\ (1 - R_{B2})]$$

Assuming only a non-transmitting mode of failure, equal reliabilities of the corresponding components in Systems I and II, and that there is no physical interaction that would change the system reliability, and given

$$R_{A1} = R_{A2} = 0.950$$

$$R_{B1} = R_{B2} = 0.900$$

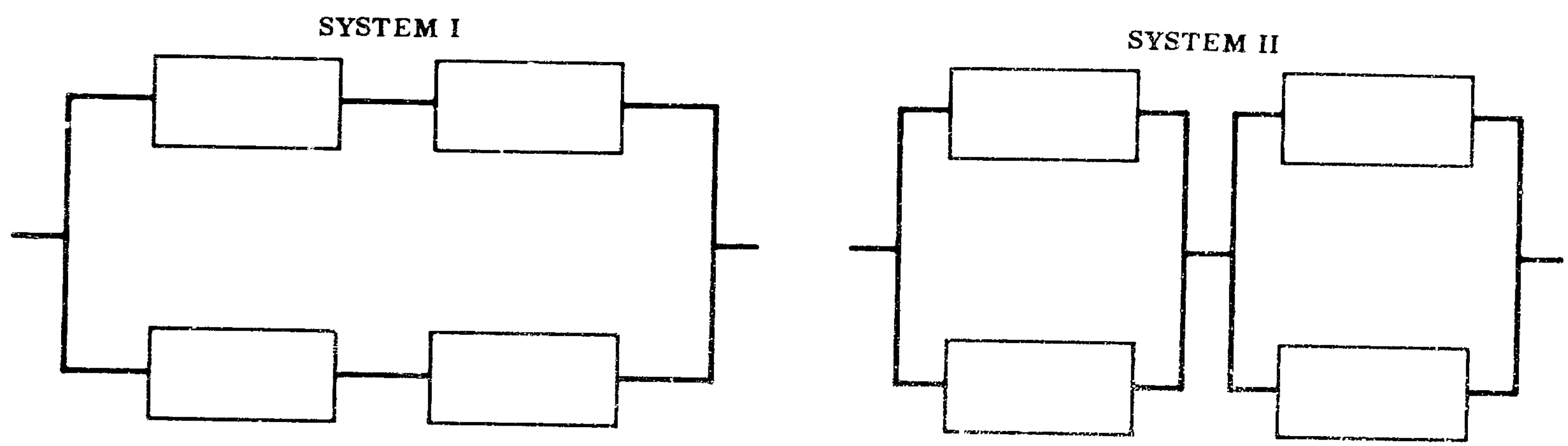
then $R_S = 1 - [1 - (1 - 0.950)\ (0.900)][1 - (0.950)\ (0.900)]$

$= 0.979$ for System I,

and $R_S = [1 - (1 - 0.950)(1 - 0.950)][1 - (1 - 0.900)(1-0.900)]$

$= 0.988$ for System II.

REDUNDANCY CONSIDERATIONS



It is possible to demonstrate mathematically that under the given assumptions the reliability of SYSTEM II is better than the reliability of SYSTEM I. The numerical results above confirm this point.

4.2 EXCEPTIONS TO SERIES PARALLEL SOLUTIONS

All reliability problems cannot be reduced to clear-cut cases of series, parallel or stand-by models. Consider the case illustrated in Figure 5-30.

A and A' are in series and so are B and B'. Paths $A-A'$ and $B-B'$ are in parallel, so that an output is present if at least one path is functioning properly. However, to improve reliability, unit C is added. Its function is to supply A' or B', if necessary, when an appropriate signal is received. C is not in parallel with A or B, and hence the circuit will not resolve to a simple parallel-series combination.

To solve the problem on hand, use can be made of Bayes probability lemma, which in terms of reliability, states:

$$Q_s = Q_s \text{ (if C is good) } R_C + Q_s \text{ (if C is bad) } Q_C$$

where Q_s denotes the probability of system failure

R_C denotes the reliability of block C

Q_C denotes the probability of failure of block C

In other words this theorem states, that the probability of failure of the complete system (no output) is the probability of the system failing if C is good, times the reliability of block C plus the probability of system failure if C is bad times the probability of C failing.

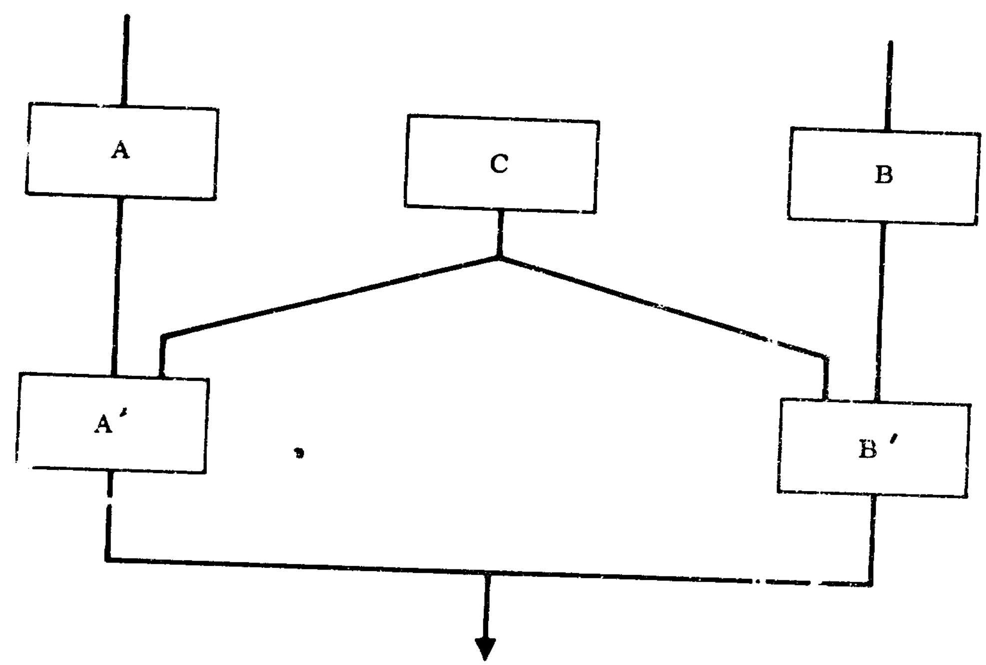
Now, if C is good, the system will fail only if both A' and B' fail. A' and B' being in parallel, the probability of system failure (the unreliability of the system) is then:

$$Q_s \text{ (if C is good) } = (1-R_{A'})\ (1-R_{B'})$$

If C is bad, the system reduces to a common series-parallel system and the probability of system failure is:

$$Q_s \text{ (if C is bad) } = (1-R_A R_{A'})\ (1-R_B R_{B'})$$

SERIES - PARALLEL REDUNDANCY EXCEPTIONS



where $(1-R_A R_{A'})$ is the unreliability of A-A′ series path, and $(1-R_B R_{B'})$ is the unreliability of B-B′ series path. The unreliability of the whole system can now be written:

$$Q_s = (1-R_{A'})\ (1-R_{B'})\ R_C + (1-R_{A'}R_{A'})\ (1-R_{B'}R_{B'})\ (1-R_C)$$

Hence the reliability of the system is:

$$R_s = 1-Q_s = 1-R_C(1-R_{A'})\ (1-R_{B'}) - (1-R_C)\ (1-R_A R_{A'})\ (1-R_B R_{B'})$$

In order to illustrate further the application of Bayes Lemma, consider the following example:

Example: A 30KV, 60 cps transmission line comes to a paper mill area and is there stepped down to a 440V by two main distribution transformers, blocks A and B (See Figure 5-32). These blocks also have circuit breakers associated with the transformers and required to protect the transformer in case of short-circuit or overload.

We assume in this case that the reliability of the transmission line is 100%. Hence we can consider A and B as two independent sources of power. A′ and B′ include the distribution equipment (circuit breakers, cabling, bus, etc.) for power supplies A and B respectively. The outputs of A′ and B′ are connected together and thus feed the load in parallel.

As in most process industries, a power failure is rather critical and will cause extensive losses, because re-starting of the plant after recovery of power cannot be immediately effected. Therefore reliability must be increased considerably by adding a third power source, C, which functions as a standby for both primary sources. C is a diesel-engine or steam-turbine-driven three phase alternator, with its two circuit breakers, CB1, CB2. Now, without block C, if, for instance, A fails, B will feed the load, but the parallel redundancy is lost. With C in the circuit a parallel redundancy is maintained if either A or B malfunctions.

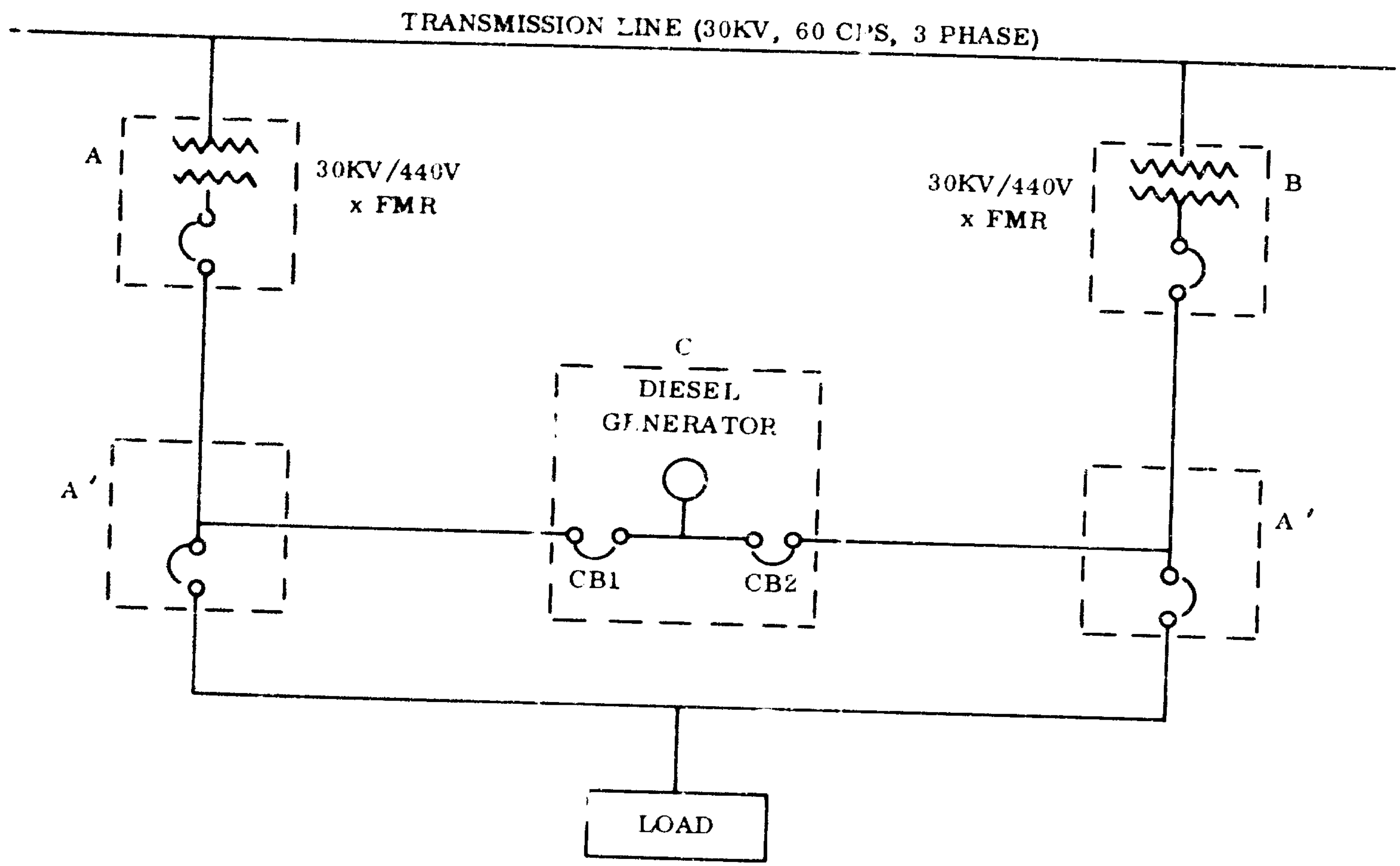
Assuming the following reliability values for the blocks A, A′, B, B′ and C, let us compute the system reliability for the cases without and with block C.

Let $R_A = R_B = 0.8$

$R_{A'} = R_{B'} = 0.9$

$R_C = 0.8$

POWER DISTRIBUTION SYSTEM



a) Without block C

$$Q_s = (1-R_A R_{A'}) (1-R_B R_{B'}) = (1-0.8 \times 0.9) (1-0.8 \times 0.9)$$

$$= 0.078$$

$$R_s = 1-Q_s = 1-0.078 = 0.922$$

b) Block C included

$$R_s = 1-R_C(1-R_{A'})(1-R_{B'}) - (1-R_C) (1-R_A R_{A'}) (1-R_B R_{B'})$$

$$= 1-0.8(1-0.9)(1-0.9)-(1-0.8)[1-(0.8)(0.9)][1-(0.8)(0.9)]$$

$$= 0.976$$

As can be seen the reliability of the system has improved about 5.4%, after block C was inserted. By comparing the decrease in unreliability, the improvement appears even more dramatic. The unreliabilities in the two cases are:

a) $Q_s = 0.078 = 7.8\%$

b) $Q_s = 0.024 = 2.4\%$

In other words the system unreliability has dropped from 7.8% to 2.4%, a factor of 3.25.

4.3 EXAMPLE OF RELIABILITY OPERATIONAL MODEL

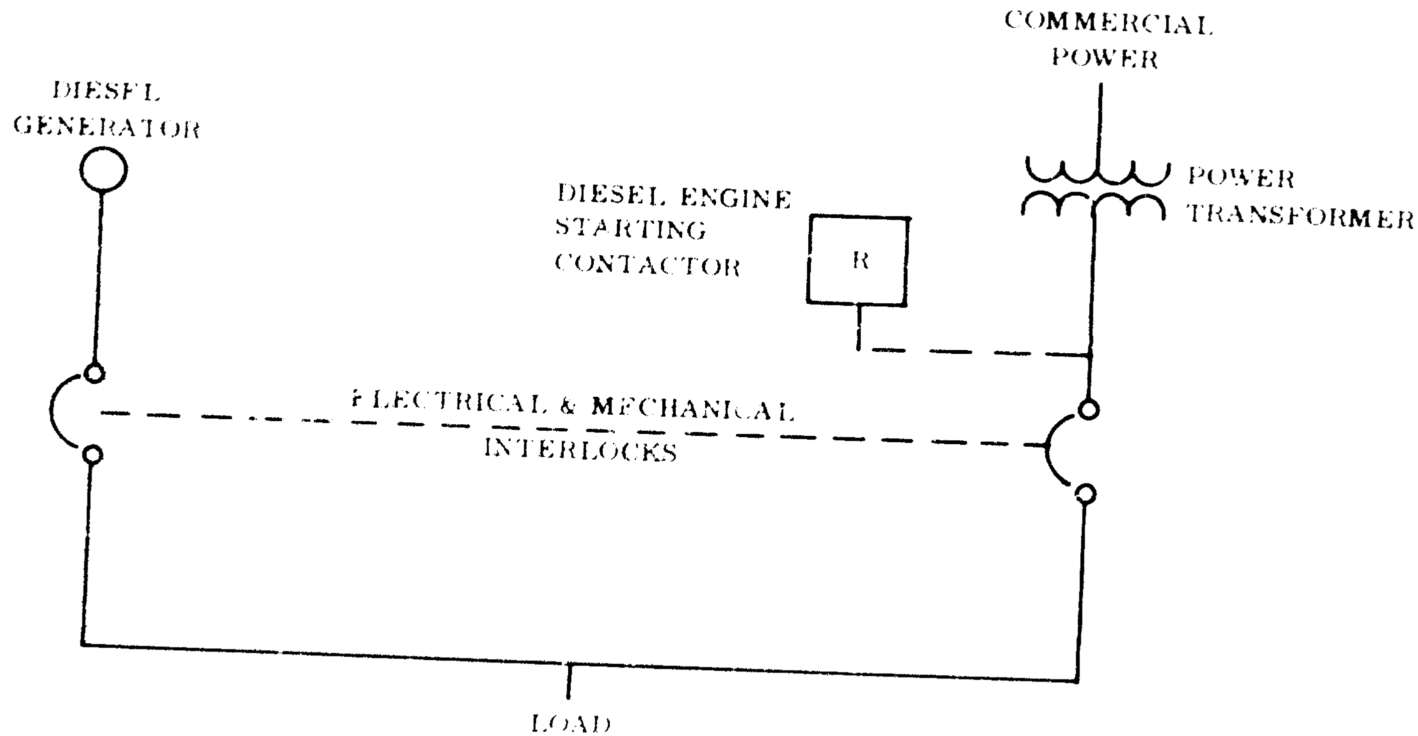
Figure 5-34 illustrates the power generation section of a ground support electrical system for a missile site. In order to evaluate the system reliability, failure rate data for all equipment in the system must be known or estimated.

The system will be broken down to subsystem or components for the purpose of establishing RFB's (Reliability Functional Blocks). The RFB's should be composed of components or subsystems, which are replaceable in the field. In the example, the RFB's shown in Figure 5-35 could be used.

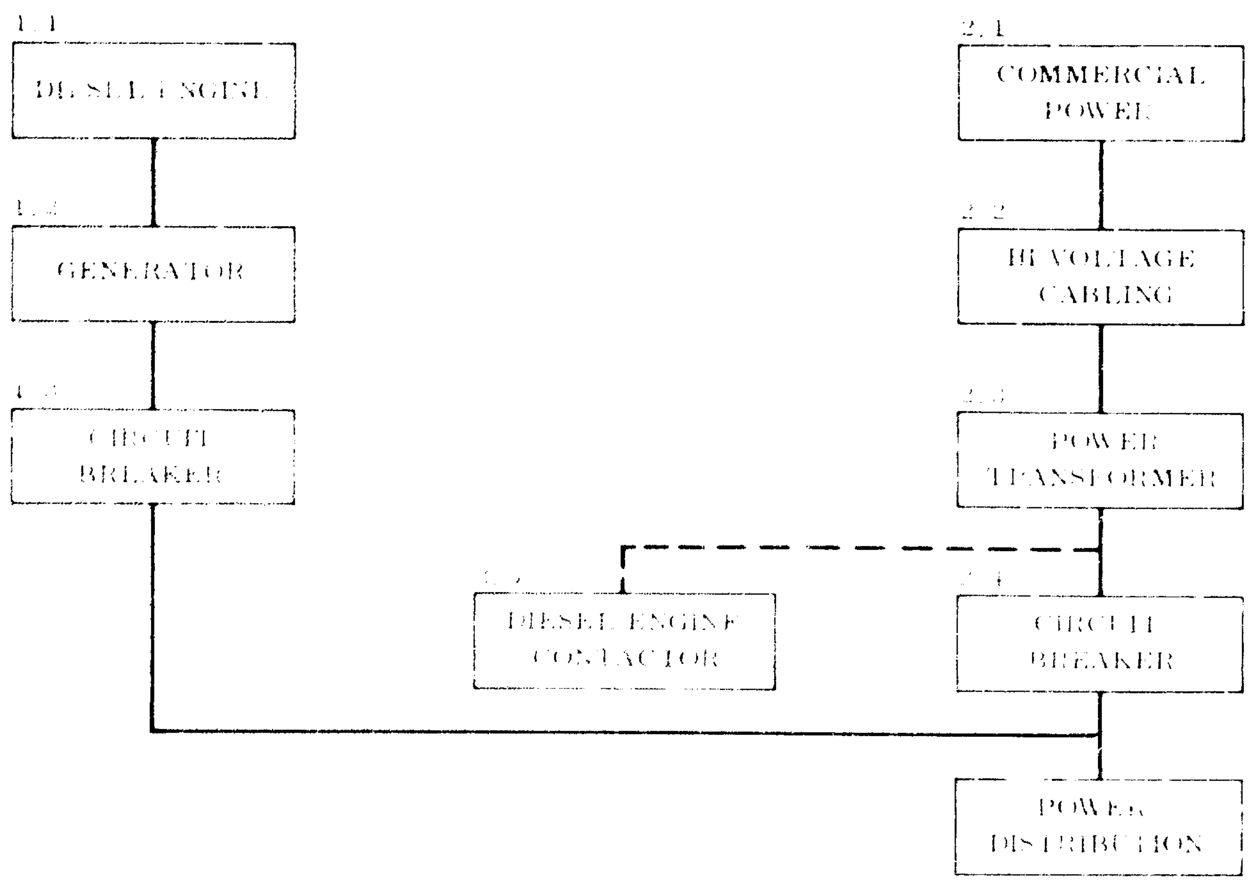
4.3.1 RFB Descriptions:

1.1 Diesel Engine: This function consists of the diesel engine, engine instrumentation board and other apparatus needed for control and monitoring the operation of the diesel engine.

POWER GENERATION SECTION



FUNCTIONAL MODEL



1.2 480 VAC, 60 CPS Generator: This function is defined as the generator itself, its controlling equipment and the apparatus necessary to transfer the generated power.

1.3 Circuit Breaker: This block contains that portion of the switchgear which carries the electric power from RFB 1.2 to the distribution bus.

2.1 Incoming Commercial Power: This function is defined to be that portion of the commercial power system to, and including, the switch on the power pole.

2.2 High Voltage Cabling: That section of the wire from pole switch to the power transformer.

2.3 Power Transformer: The step-down transformer.

2.4 Circuit Breaker: That portion of the switchgear which carries the commercial power to the main bus.

2.5 Diesel Engine Starting Contactor: This block consists of the diesel engine starting contactor and the wiring connecting it from the low side of step down transformer.

4.3.2 Logic Diagram: Having the reliability functional block diagram and the description of the RFB's, we are able to construct the mathematical model for the system under study. The model consists of a logic diagram and equations giving the reliability in terms of failure rate λ and operating time t of each functional block (RFB).

4.3.3 Reliability Equation: This problem is a case of standby redundancy with repair. Therefore the reliability for time t may be stated:

$$R_s = 1 - \sum_{i=1}^{n} \left[\frac{\left\{(\lambda_{2.1} + \lambda_{2.2} + \lambda_{2.3})[t-T(i-1)]\right\}^{i}}{i} e^{-(\lambda_{2.1}+\lambda_{2.2}+\lambda_{2.3})[t-T(i-1)]} \right] \left[\left(1 - e^{-\left(\frac{\lambda_{1.2}}{2} + \frac{\lambda_{2.4}}{2} + \frac{\lambda_{2.5}}{2}\right)t}\right) + e^{-\left(\frac{\lambda_{1.2}}{2} + \frac{\lambda_{2.4}}{2} + \frac{\lambda_{2.5}}{2}\right)t} \left[1 - e^{-(\lambda_{1.1} + \lambda_{1.2})Ti}\right] \right]$$

where T is the mean time to repair for blocks 2.1-2.3.

4.3.4 Failure Rates: It is assumed that the following data for failure rates have been collected from tests and previous case histories of component failure.

$\lambda_{1.1}$ = 4.08830 failures/1000 hours

$\lambda_{1.2}$ = 0.40883 failures/1000 hours

$\lambda_{1.3}$ = 0.1000 failures/1000 cycles

$\lambda_{2.1}$ = 0.68493 failures/1000 hours

$\lambda_{2.2}$ = 0.11415 failures/1000 hours

$\lambda_{2.3}$ = 0.22831 failures/1000 hours

$\lambda_{2.4}$ = 0.10000 failures/1000 cycles

$\lambda_{2.5}$ = 0.66667 failures/1000 cycles

T = 2.000 hours

4.3.5 Operating Times: Definition of the operating conditions for each RFB is generally required.

1.1 Diesel Engine I: This unit is operating during the interval when it is started until it is stopped.

1.2 480 VAC, 60 CPS Generator I: This unit is considered operating whenever RFB 1.1 is operating.

1.3 Circuit Breaker I: This unit operates whenever there is a failure of the commercial power or when it is manually operated. A complete cycle is defined as the movement of the breaker to OFF and back to ON position.

2.1 Incoming Commercial Power: This function is considered operating whenever there is commercial power available for use at the site.

2.2 High Voltage Cabling: This function is considered operating whenever RFB 2.1 is operating.

2.3 Power Transformer: This function is considered operating whenever RFB 2.2 is operating.

2.4 Circuit Breaker: This unit operates simultaneously with RFB 1.3.

2.5 Diesel Engine Starting Contactor: This unit is considered operating whenever RFB 1.3 operates. It is also a cyclic function.

4.3.6 Time Bar Graph: From the definitions above, we can now construct the time bar graph (Figure 5-29). Note that blocks 1.3, 2.4 and 2.5 operate only at fault in the primary (commercial power) system and at its recovery. In this case, there is no function which is turned "off" or "on". However, this is not the usual occurrence and in cases where switching takes place, it is less confusing and easier to make the model if a time bar graph is used.

4.3.7 System Reliability: Substituting the failure rate values and operating times in the pertinent equations, the system reliability for an operating period of 30 days is:

$$R_s = 1 - \sum_{i=1}^{360} \left[\frac{\left\{1.02739[0.720-0.002(i-1)]\right\}^i}{i} e^{-1.02739[0.720-0.002(i-1)]} \right]$$

$$\left[1 - e^{-0.76667i} + e^{-0.76667i}\left(1 - e^{-4.49713 \times 0.0002i}\right)\right]$$

$$= 0.9928$$

For the sake of illustration, let us compare the reliability of system 2.0 above, that is without the standby redundancy, to that just computed. The reliability without standby redundancy is

$$R(s) = e^{-(\lambda_{2.1} + \lambda_{2.2} + \lambda_{2.3})t} = e^{-(0.68494 + 0.11415 + 0.22831)0.72}$$

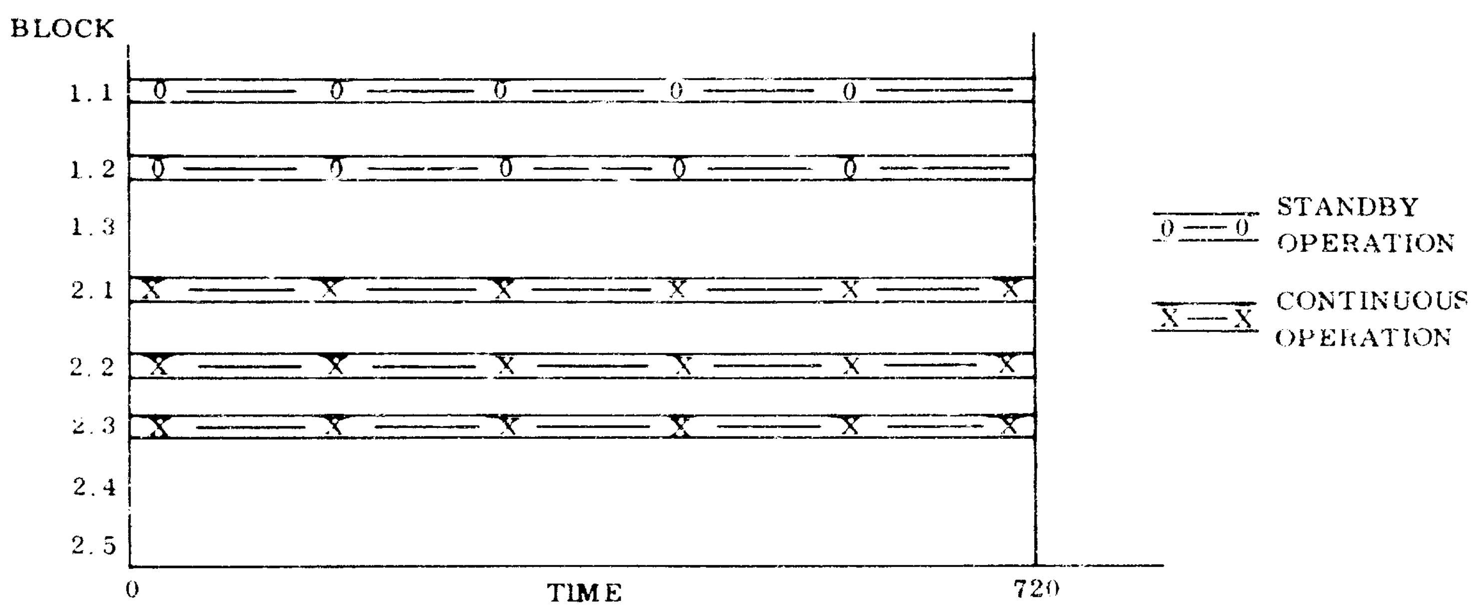
$$= e^{-0.73972} = 0.4772$$

Thus the reliability has increased from 47.72% to 99.28% by using standby redundancy with repair.

4.4 SUMMARY

The purpose of reliability predictions is to arrive at a numerical evaluation (quantitative) of the reliability potential of a system, equipment, etc., and/or to determine whether or not a specific system, equipment, etc., will meet its predetermined or required reliability goal. It is necessary to perform these reliability predictions during the design stage. This enables the design to be evaluated in terms of reliability and allows design changes which may be needed to improve reliability to be made at this early stage where it is most economical as well as convenient.

TIME BAR GRAPH



It should be remembered that reliability predictions can be made at various complexity levels. The selection of method to be used is determined by such factors as required accuracy, time available, cost, etc. However, no matter which method is used in calculating a reliability prediction, it must be based on design details and on reliability or failure rate data of equipments or parts of similar design and under similar operating conditions of stress, time, and environment.

5. RELIABILITY GROWTH APPROACH

The reliability prediction as made is called inherent. This refers to some future time when the design is matured -- has all the weaknesses and defects due to manufacturing cleared out. We are bound to be concerned with the reliability achieved during the development. We are particularly concerned that we obtain visibility of reliability growth toward the deliverable requirement. Recognizing that the growth process is the process of isolating and eliminating weaknesses, there is a real need to evaluate progress toward the goal. In dealing with contractors we can expect some to develop growth predictions as a basis for further development or continuation of a project.

The promise of improvement can be validated. In evaluating such promise we must look at the physical basis on which it is founded. The basic philosophy and foundation of growth models is provided to give a basic understanding of the concepts.

5.1 RELIABILITY GROWTH MODELS

One approach to construction of a reliability growth model is to postulate the form of the function relating reliability and time, say $R = f(t)$. The argument t could represent any index of reliability growth such as the number of reliability tests conducted on the device, the time since the development of the device began, the amount of money invested in the development, etc. Having assumed such a relationship, one proceeds to estimate the parameters of the function by some curve fitting technique, analogous to the procedures utilized in linear regression. When this approach is taken, a function having the following properties is usually selected.

$f(t)$ is nondecreasing in t (reliability growth)

$f(t)$ approaches R_∞ as t approach ∞ where R_∞ is the maximum attainable reliability. A function meeting this criterion is, for example, $R(t) = R_i - C'e^{-Kt}$. This particular form of the equation states that the reliability at time t, R(t) is limited by the inherent (predicted) reliability and will approach that value as tests are conducted at a rate proportional to the gap between the actual and predicted reliabilities.

In development programs it is generally supposed that, given a basic design, reliability can be improved through a "test and fix" procedure. That is, as causes of failure are detected by tests, action can be taken to correct the cause of the failures - action which is not always effective. The causes of the greater numbers of failures will probably be detected early in the program, and consequently, have the greater chance of being corrected early. This tends to justify the general form of the reliability growth curve in which reliability increases rapidly in the early stages with the rate of increase diminishing with time. The notion of inherent design reliability, i.e., the limit which the growth function approaches in time, can be justified in a similar manner. Designs which inherently contain many causes of failure, most of which will cause only a small number of failures, would have a low design reliability. After the principal causes of failure are eliminated early in the program, each "test and fix" cycle will only improve reliability a very small amount. Eventually, the reliability curve will tend to level out. This level approaches the inherent design reliability.

Another approach to a growth model is given in reference (1). A fixed, but unspecified, number of failure modes are allowed to exist. Whenever a failure mode is discovered by test, an attempt is made to correct the cause. The probability that the corrective action is successful for the ith failure made is a known quantity a_i. That is, the probability of correcting the ith failure mode, given that such a failure has occurred on test, is a_i. In this model, N tests are conducted prior to taking any corrective action. The reliability of the system after N tests have been made and corrective action has been taken for all detected failure modes is

$$R_N = R_O + \sum_{i=1}^{K} y_i q_i$$

where

$$y_i = \begin{cases} 0 & \text{if } N_i = 0 \\ a_i & \text{if } N_i > 0 \end{cases}$$

N_0 = total number of failures observed in N tests = $\sum_{i=1}^{K} N_i$

N_i = number of failures of the ith mode observed during test

K = number of failure modes

q_i = probability of a failure of the ith mode

R_0 = initial reliability of system.

It is assumed that a given test can result in success with unknown probability R_0, or in failure by only one of the K failure modes and

$$R_0 + \sum_{i=1}^{K} q_i = 1.$$

The parameters of this model are R_0 and the K q_i's. The a_i are assumed known. The random variables resulting from tests are N_0, N_1, N_2, ..., N_K. It is assumed in the analysis that the tests are independent. It is easily seen that this model is, in a sense, a generalization of the Lloyd and Lipow model (2) in that reliability growth is obtained by taking credit for having corrected some of the original causes of failure.

From a practical point of view, this model has some real value. It appears to be a reasonable representation of some real world situations, and its use requires input data which in many cases will be available. It is not too hard to envision situations where an engineer can, based on his previous experience, estimate fairly accurately the probability (a_i) that a corrective action will be effective. It should be noted that this estimate is required only when a corrective action is actually taken. It is significant that both of these decisions (selection of the a_i and the likelihood that a corrective action will introduce other modes of failure) can be framed in physical terms as engineering questions.

5.2 APPLICATION OF GROWTH APPROACH

The use of reliability growth approaches promises the gradual elimination of quality defects. They are effective insofar as the trend toward higher reliability improves. They should be used with caution unless solid engineering or test data confirm that the growth is real.

6. PURPOSES FOR RELIABILITY PREDICTION

A primary means of establishing the reliability feasibility of a design concept is the comparison of pre-design predictions with requirements. The consideration of the direction, magnitude, and causes of discrepancies between predictions and requirements plays an important role in determining proper courses of action. A basic problem in reliability prediction can be generally described as follows: Given a complex device or system, such as a communication set, fire control, sonar or computer, at some stage of design and development, we are interested in whether or not it will function in a given environment, in a prescribed manner, and for a given period of time. Whether the system operates successfully or not depends on a very large number of factors. When predicting the reliability of a given complex equipment, if possible, one should evaluate the interactions present since these may have a preponderant effect on the over-all system reliability.

Reliability predictions aid in the identification and solution of problems that are broad in scope and general in nature. This is accomplished by the tabulation and grouping of predicted reliabilities, or unreliabilities, for specific part types, part classes, and equipment types, and for operation in various modes or during different phases of a mission. The knowledge of the relative contribution of various items of equipment and modes of operation to the systems unreliability constitutes a sound basis for determining the need for, and the expected benefits of, part improvement programs, circuit and equipment redesign efforts, inclusion of redundancy, reallocation of requirements, and other similar courses of action.

Another valuable use of reliability predictions is to focus attention on items for which adequate design data are not available. It will frequently be found that necessary failure information is not available. This is especially true for new parts and parts peculiar to a specific application. The process of reliability prediction uncovers these data deficiencies and permits early planning for corrective action, i.e., revision of specification, selection of a different part, starting a data collection program, or performing special tests.

An obvious purpose of reliability predictions is to serve as a means to measure progress in achieving a reliability goal, i.e., comparison of predictions with previous predictions to see whether a program is progressing satisfactorily or not. If the program is progressing satisfactorily, it may be decided that the activities should continue as planned. However, if progress is not satisfactory, the predictions may be used to determine what action should be taken as well as where the re-emphasis should be.

7. REFERENCES

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Chapter 6

APPORTIONMENT

Chapter 6

APPORTIONMENT

System design engineers must translate overall system characteristics, including reliability, into detailed specifications for the numerous units that make up the system. The process of assigning reliability requirements to individual units to attain the desired system reliability is known as "reliability apportionment" or sometimes termed reliability allocation. More is involved, however, than a simple mathematical equality. The reliability of an individual unit varies with the type of function to be performed, the complexity of the unit, and the method of accomplishing the function, to name a few of the more important factors. The role a unit plays in a particular system also enters into consideration.

Apportionment of system reliability is the inverse process to a reliability prediction. In a prediction we estimated failure rates of parts and subsystems (or numbers of failures per unit of time) and computed a system failure rate (total number of failures estimated per unit of time). In an apportionment we start with a requirement, which is converted to total failures to be permitted per unit of time. We then allocate to the various subsystems a share of the failures to be permitted. The apportionment in no sense indicates that the particular level of reliability required can be achieved. It merely says that if the apportioned values are achieved, the system will meet its requirements.

To make the apportioned values of reliability realistic, consideration must be paid to the factors making reliability difficult or expensive to achieve. The development of high reliability is costly. Establishing requirements higher than necessary is uneconomical. Apportionment techniques should be based on the factors that define the relative effort and cost of achieving the required reliability for the system.

The apportionment of system reliability involves solving the basic equality

$$f(\hat{R}_1, \hat{R}_2, \ldots \hat{R}_n) = R \qquad (6\text{-}1)$$

where

$\hat{R}_i$ is the apportioned reliability parameter for the ith unit,

R is the system reliability requirement parameter, and f is the functional relationship between unit and system reliability.

For a simple series system in which the $\hat{R}_i(t)$s represent probability of survival for t hours, Equation 6-1 becomes

$$\hat{R}_1(t) \cdot \hat{R}_2(t) \ldots \hat{R}_n(t) = R(t) \tag{6-2}$$

Theoretically, Equation 6-2 has an infinite number of solutions, assuming no restrictions on the apportionment. The problem is to establish a procedure that yields a unique or limited number of solutions, by which consistent and reasonable reliabilities may be allocated.

The program and methods presented in this chapter can apply to the sub-allocation of reliability within the various units. The apportionment program is necessarily one of continual refinement. Original requirements determined at the design stage should be critically examined and revised as more experience, knowledge, and test data become available during the advance of the system life-cycle through the design, development, and production phases.

1. APPORTIONMENT OF INHERENT RELIABILITY

1.1 BASIC THEORY

In Chapter four we developed the statement of reliability in terms of probability of success based on a failure density function. A failure density function can be determined for any set of equipment.

It has been shown that the probability of success (the reliability) of a system is the probability that no failure occurs during the time in question. In the general case the reliability may be stated

$$\hat{R}_i = \exp\left[-\int_{t_1}^{t_2} F_i(x)\,dx\right] \tag{6-3}$$

where the $F_i(x)$ is the instantaneous hazard function. Where the distribution function is exponential, this hazard function is the "constant" failure rate λ. In the normal case, it is the ordinate of the normal curve

$$n(a) = \frac{1}{\sqrt{2\pi}\,\sigma}\, e^{-\frac{1}{2}\left(\frac{a-\mu}{\sigma}\right)^2}$$

In conducting an apportionment, we start with defining our system as a series of units so that equation 6-2 applies. Where equipments are duplicated in parallel, it is necessary to treat the combination as a single unit. Applying equation 6.3

$$R = \exp\left[-\int_0^t F_1(x)\,dx - \int_0^t F_2(x)\,dx - \ldots - \int_0^t F_n(x)\,dx \right]$$

$$= \exp\left[\sum_{L=1}^{w} -\int_0^t F_i(x)\,dx \right]$$

If we set $\hat{R}_i = R^{a_i}$ and solve for the a_i

$$a_i = \frac{-\int_0^t F_i(x)\,dx}{\sum_{i=1}^{w} -\int_0^t F_i(x)\,dx} \qquad (6\text{-}4)$$

the a_i factors have the following characteristics:

(a) $\sum_{i=1}^{n} a_i = 1$

(b) Each a_i is the fraction that represents that portion of the total probability of failure in the system attributable to the ith unit.

We can apportion the reliability by selecting factors for each unit (the a_i) such that (a) the sum of the factors add to 1 and (b) each factor is the fraction of the failures allowed for the system to be permitted to the unit.

1.2 SELECTION CRITERIA

The ideal apportionment would be that allocation of requirements resulting in the most economical use of resources, including time and cost. Among others, the following considerations should be considered.

(a) The complexity of the system will have an effect on the achievable reliability. The more complex the system is, the greater the number of subassemblies and modules, the more difficult and costly it is to achieve a high reliability. Imposing an unrealistically high reliability on the more complex systems increases the cost disproportionately when compared with the effect of increasing the reliability requirement for simpler systems.

(b) The amount of development and research required to produce the system will greatly influence the time and cost of development. Imposition of a high reliability requirement on a system under development will increase the development time, numbers of tests required to obtain the reliability and the cost. Equipments considered present "State of the Art" are penalized less by high reliability requirements.

(c) The intended operational environment will have an effect on the achievable reliability. A system to be used in a "rugged" environment will tend to cost more to develop to an equal reliability than a similar one to be used under less severe conditions.

(d) The length of time the equipment is required to perform will influence the achievable reliability. It will require more development effort and cost to produce a system capable of operating for a long period of time without failure than to develop one for a shorter period of use.

(e) The need for high reliability in a system is based on the importance of its operation. A system whose failure would not jeapordize the accomplishment of the mission need not be highly reliable. To the extent that failures can be tolerated, lower reliability requirements should be imposed.

Apportionment of reliability is a trade-off between the reliabilities of units to achieve a specified system reliability. By imposing high reliability requirements on those units in which high reliability is easier to attain, and lower requirements on those in which high reliability is more difficult and more costly, the overall cost of the system development may be reduced.

Numerous methods have been used to select the factors for the opportionment to achieve this cost (and time) improvement.

2. TECHNIQUES OF APPORTIONMENT

2.1 EQUAL APPORTIONMENT

In the absence of any definitive information on the system, other than the fact that a subsystems will be used, the only rational basis to use would be equality. If each a_i is set at $1/N$, the two requirements are met. Each subsystem is then required to have a reliability of $(R)^{1/N}$ or $\sqrt[N]{R}$. The product of the N system reliabilities is then $(\sqrt[N]{R})^N = R$.

2.2 CONSIDERATIONS OF IMPORTANCE AND COMPLEXITY

Task group 2 of the AGREE Study (1) recommends an apportionment for electronics systems based on the importance of the unit and its complexity. The exponential distribution of times to failure is assumed to apply. Let a system consist of k units. For i = 1, 2 .. k let

m_i = MTBF (mean life) of the ith unit.

t_i = Operating time during the mission required of the ith unit.

w_i = Probability that the system will fail, given that the ith unit fails (importance factor).

n_i = number of modules (e.g., tubes) in the ith unit.

N = Total number of modules in the system = $\sum_{i=1}^{k} n_i$

It is desired to apportion the reliability between the units in such a manner that each module make an equal contribution to mission success. The mean life to be required for each equipment is computed from the formula

$$m_i = \frac{w_i t_i}{\left(\frac{n_i}{N}\right)(-\ln R)} \tag{6-5}$$

Example: For a system reliability requirement of R=.90(-LnR=.103)

	n	w	t	m
RCVR	20	.7	4 hrs	402
XMTR	30	.5	4 hrs	218
RADAR	200	.8	4 hrs	52
IFF	50	.2	4 hrs	52
N	300			

The equation for the reliability of the ith unit is:

$$R_i = e^{-t_i/m_i}$$

We can rewrite 6-5 to show:

$$t_i/m_i = \left(\frac{n_i}{N}\right)\left(\frac{1}{w_i}\right)(-\ln R)$$

So,

$$e^{-t_i/m_i} = (R)^{\left(\frac{n_i}{N} \cdot \frac{1}{w_i}\right)}$$

This equation shows that the basis of the factors a_i in equation 6-4 are made up of the product of numbers representing the relative complexity of the equipment and numbers representing the importance of the unit to mission success.

2.3 FURTHER EXTENSION TO MECHANICAL-ELECTRICAL SYSTEMS

The Boeing Company, in its Reliability Manual (2) proposes an alternate method of selecting the factors of apportionment. The parameters to be considered are:

(a) System Complexity: Complexity is evaluated by considering the probable quantity of parts or components making up the system, and is also judged by the assembled intricacy of these parts or components. The least complex system is rated at 1. The system considered highly complex is rated at 10.

(b) State of the Art: The state of present engineering progress in all fields is considered. The system least developed is assigned a value of 10 and the system most highly developed is assigned a value of 1. All other systems are evaluated between 10 and 1.

(c) Performance Time: The system that operates for the entire mission time is rated 10, and the system that operates a minimum time during the mission is rated at 1. All other systems are evaluated between these two extremes.

(d) Environmental Conditions: Environmental conditions can also be rated from 10 through 1. Systems expected to experience harsh and extreme conditions during performance will be classified as 10 and systems expecting to encounter the least severe conditions will be classified as 1. All other systems shall lie between these two extremes.

A typical computation is shown in Figure 6 [illegible] ne selection of the factors is done by engineering judgment based on the engineers

MECHANICAL-ELECTRICAL SYSTEMS

SYSTEM	COMPLEXITY	STATE OF THE ART	PERFORMANCE TIME	ENVIRONMENTS EXTREMES	PRODUCT	a_i	R_i
PROPULSION	5	6	5	5	750	.098	.9895
ORDNANCE	7	6	10	2	840	.109	.9886
GUIDANCE	10	10	5	5	2500	.324	.9664
FLT. CONTROL	8	8	5	7	2240	.289	.9700
STRUCTURE	4	2	10	8	640	.083	.9913
AUX. POWER	6	5	5	5	750	.098	.9895

Sum of Products 7720

To apportion a system reliability of 0.90 between six systems.

$$R = 0.90$$

$$R_i = (0.90)^{a_i}$$

$$a_i = \frac{\text{Product}}{\text{Sum of Products}}$$

predictions of the relative effect of various factors on the reliability of performance of the system. Using a philosophy that there are no new components, new systems are rearrangements of known components. The engineer would judge what types of parts and components would be used in a new system and what effect the expected use of these parts would have on the reliability of the parts. Where particular components had, in his experience, been unreliable in a particular environment, he would reflect this in his choice of factors. Factors may be selected by individual engineers or through some form of voting technique as described in paragraph 3.

2.4 EXTENDED METHOD FOR ELECTRONICS SYSTEMS

A further development of the AGREE system (2.2) has been made by Arinc Corporation (3).

2.4.1 Elements Considered in the Apportionment:

(a) Unit Essentiality: The concept of essentiality, used to describe the effect of unit failure on mission success, is considered unity if a failed unit does not have a functional duplicate. It is defined as follows:

> The essentiality of a unit is the probability that the system will fail to accomplish its mission if the unit fails while all other units perform satisfactorily.

At the design stage of system development, the likelihood is that the essentiality of various units within the system will have to be assigned intuitively, on the basis of experience gained with similar systems. If appropriate system failure data is available, essentiality can be estimated by the ratio,

$$E_i = \frac{\text{Number of mission failures due only to ith unit failure}}{\text{Number of ith unit failures}}$$

(b) Basic Failure Data: The allocation procedure is based on the relative reliabilities to be expected of various units of a system, as determined from past experience. The electronic functional levels to which this procedure is applicable correspond to the functions performed by individual element groups (AEG's). An active element group is defined as consisting of an active element (one part, such as a tube, capable of performing valving or controlling action) plus the associated passive parts; examples of active element groups include amplifiers, oscillators, mixers, and rectifiers. Equivalents are provided for non-electronic components.

2.4.2 Procedure for Reliability Apportionment: The worksheet used for conducting an apportionment is given in Figure 6-11.

Steps in completing the worksheet are:

(a) Identify the units, U_i

(b) Estimate the essentiality index (paragraph 2.4.1b), E_i

(c) Record or estimate that portion of the system operating time the unit will be required to operate, t_i

(d) Develop unit failure indices, K_i, based on class of equipment, relative failure rates for the class and number of modules of the class in the unit (refer to reference 3).

(e) Compute the failure index ratio $w_i = \dfrac{K_i}{\sum_{i=1}^{n} K_i}$

(f) Compute the allocated unit reliabilities from the equation

$$\hat{R}_i = 1 - \frac{1 - (R)^{w_i}}{E_i}$$

where $\hat{R}_i$ is the desired reliability apportioned to the ith unit,

R is the system required reliability.

Figure 6-12 shows a typical computation of the unit failure indices. The system is a bombsight consisting of three units, power supply, navigation computer and optical equipment. The units are considered in modified series, since both the power supply and optical equipment must work. In the event the navigation computer should fail the optical equipment can be controlled manually. The essentiality of the power supply and optical equipment are unity. On the basis of performance of similar systems, estimates were made that for every 100 missions in which the navigation computer failed, 57 mission failures resulted. So the essentiality of the navigation computer was estimated at 57/100 = .57.

RELIABILITY ALLOCATION WORKSHEET

DESIGN STAGE

System ____________________ Date ____________

Primary Mission ____________ System Operating Time - T ____________

System Reliability Requirement ____________

Unit or Configuration Identification	U_i		U_1	U_2	. . .	U_m
Essentiality	E_i		E_1	E_2	. . .	E_m
Operating Time	t_i		t_1	t_2	. . .	t_m
Failure Index	K_i		K_1	K_2	. . .	K_m
Failure Index Ratio	w_i		w_1	w_2	. . .	w_m
Allocated Reliability	$\hat{R}_i$		$\hat{R}_1$	$\hat{R}_2$	. .	$\hat{R}_3$

DATA WORKSHEET FOR DETERMINING UNIT FAILURE INDICES, k_j

	i	Function	k'_i	k_i	Unit #1 Power Supply k_{i1}	Unit #1 Power Supply f_{i1}	Unit #2 Computer $\bar{k}_{i2}$	Unit #2 Computer f_{i2}	Unit #3 Optical Equip. $\bar{k}_{i3}$	Unit #3 Optical Equip. f_{i3}	Functional Totals f_i	Functional Totals $f_i k_i$
Group a	1	Primary Power		4.3	4.3	40					40	172
Group a	2	Pulse, Low Power		3.0			3.0	10			10	30
Group a	3	Pulse, Low Power (Trans)		3.0			0.9	230			230	690
											$F_e = 280$	$K_e = 892$
			k'_i	$k_i = \bar{K}_e k'_i$							$\bar{K}_e = 3.186$	
Group b	4	Synchro, Resolver	0.70	2.23			2.23	35	2.23	5		
Group b	5	Gyro	12.10	38.55			38.55	1				
Group b	6	Prism	0.55	1.75					1.75	3		
Group b	7	Thermostat	0.20	0.64			0.64	25	0.64	3		
Group b	8	Motor	1.50	4.78			4.78	40	4.78	2		
Group b	9	Dehydrator	19.20	61.17			61.17	1	61.17	1		
Group b	10	Relay	0.70	2.23	2.23	3	2.23	70				
Group b	11	Relay, Stepping	8.55	27.24	27.24	1						
Group b	12	Counter	0.01	0.03			0.03	12	0.03	3		
Unit Failure Index, $K_j = \sum_{i=1}^{12} \bar{k}_{ij} f_{ij}$					$K_1 = 205.9$		$K_2 = 778.4$		$K_3 = 89.1$			

Proceeding,

Step 1: The functional category column is divided into electronic and non-electronic groups.

Step 2: The relative failure rates (K_i or K_i') for each functional category is entered in the appropriate column.

Step 3: The number of estimated AEG's of each category within each unit is entered in the column headed f_{ij} (j=1,2,3) and the electronic category rows are summed to obtain the entries in the column headed f_i.

Step 4: The average electronic failure index is computed in the following manner:

(a) Form the total unadjusted electronic failure index

$$K_e = 40(4.3) + 10(3.0) + 230(3.0) = 892$$

(b) Determine the number of electronic AEG's in group (a).

$$F_e = 40 + 10 + 230 = 280.$$

(c) Form the average electronic failure index:

$$\bar{K}_e = 892/280 = 3.186.$$

Step 5: Convert each k_i' to a failure rate relative to the electronics group by multiplying the relative failure rates by $\bar{K}_e = 3.186$. Enter in the k_i column.

Step 6: Adjusted relative failure rates, $\bar{k}_{ij}$

(a) Transfer the k_i's to the appropriate unit column;

(b) k_1 and k_2 remain unaltered for Group (a), but since k_3 in Unit 2 has a transistor active element, using an adjustment factor of 0.3, compute $\bar{k}_{32} = (0.3)k_3 = 0.9$.

Step 7: Unit failure indices

Using the formula $K_j = \sum_{i=1} f_{ij}\bar{k}_i$ for the failure index of the jth unit, compute k_i, k_j and k_i.

Step 8: The values for the unit failure indices are entered in the allocation worksheet, Figure 6-15

Step 9: Entering the allocation worksheet with the failure indices, compute the failure index ratio

$$w_i = \frac{k_i}{\sum_{i=1}^{a} k_i}$$

Step 10: The reliability apportionment $\hat{R}_i$ is computed for each unit using the formula $\hat{R}_i = 1 - \frac{1 - R^{w_i}}{E_i}$

2.5 ALTERNATE BOEING METHOD

For an alternate method of selecting the apportionment, the following approach (4) is proposed by F. E. Marsh, the Boeing Company. Given a reliability goal, R, for an item comprising n units in series and assuming an exponential distribution of times to failure, the reliability goal, R_i, apportioned to unit i is:

$$R_i = (R)^{w_i}$$

where: $w_i = \frac{a_i}{\sum_{i=1}^{w} a_i}$ and

$$a_i = I_u \, (I_K + I_f + I_m)$$

where I_u = Index of state of the art, computed using engineering data on system reliability growth rates;

I_k = Index of complexity, computed to account for relative complexity and redundancy of the unit;

I_f = Index of environment, computed from estimates of unit stress levels due to environmental conditions, and

I_m = Index of operating time, computed from the operating time of the unit and the operating time for the system.

DATA WORKSHEET FOR APPORTIONMENT

System: I

Date: ____________

Mission: Bomb Navigation

System Operating Time: 6 Hrs.

System Reliability Requirement: 0.94

Unit or Configuration Identification	U_i	Power Supply	Computer	Optical Equipment
Essentiality	E_i	1	.57	1
Operating Time	t_i	6 hr	6 hr	6 hr
Failure Index	K_i	205.9	778.4	89.1
Failure Index Ratio	w_i	.192	.725	.083
Allocated Reliability	$\hat{R}_i$	.988	.923	.995

2.6 USE OF COST OF ACHIEVEMENT

It is reasonable to assume that if a contract for a system is let with no reliability requirement, a system built in accordance with standard design practices will result. If a reliability requirement is imposed, the system will cost more by virtue of the fact that additional effort is required by the contractor. How much more the system will cost will depend upon two basic factors.

(a) By what degree the reliability requirement exceeds that expected (that experienced using standard design).

(b) The complexity of the system contracted for.

Bird Engineering Research Associates, Inc. (8) found in past procurements a relationship between the cost and reliability of equipments and their relative complexity.

$$\left.\begin{aligned} m &= 187{,}000\ N^{-1.39} \\ C &= (.891)\ (29698) N^{.88} \end{aligned}\right\} \qquad (6\text{-}6)$$

Where m was the achieved MTBF, c the contract cost and N the number of active element groups as defined by MIL STD 756. The constants apply to shipboard equipment.

For an improved product, experience (Chapter 26) indicates a relationship between cost and reliability of the form

$$C' - C = C \ln \left(\frac{m'}{m}\right)^{0.2} \qquad (6\text{-}7)$$

Where the prime is used to distinguish between an equipment produced under a different level of reliability effort. If we assume a particular requirement, R, for the reliability of the complete system, this is achievable by any combination of subsystem reliabilities, R_i that satisfy the relationship.

$$R = \prod_{i=1}^{k} R_i$$

For a system consisting of three serial subsystems $R = R_1 \times R_2 \times R_3$, where the subscripts refer to the subsystems

$$= e^{-(t_1/m_1' + t_2/m_2' + t_3/m_3')}$$

assuming an exponential distribution of times to failure. The exponent must satisfy the relationship

$$- \ln R = t_1/m_1' + t_2/m_2' + t_3/m_3' = \sum_{i=1}^{3} t_i/m_i' \qquad (6\text{-}8)$$

As may be seen from Figure 6-18, the selection of a particular set of requirements for reliability imposes a particular cost on the development program. A higher reliability requirement for any system tends to increase the cost for that system. Lowering the requirement should reduce the cost. Those in which the incremental cost of improvement is greatest should be given lesser requirements, increasing the requirements correspondingly for those with lesser incremental costs. This can be done as follows:

The total cost of the program would be the sum of costs of developing the individual systems with the conventional program costs plus the additional cost for each system necessary to improve the reliability to achieve the system reliability, R. We can define this additional cost,

$$\Delta C_R = C_1 \ln\left(\frac{m'}{m_1}\right)^{0.2} + C_2 \ln\left(\frac{m_2'}{m_2}\right)^{0.2} + C_3 \ln\left(\frac{m_3'}{m_3}\right)^{0.2} \qquad (6\text{-}9)$$

To obtain the minimum cost that will achieve the required system reliability, we can differentiate the equation below and set it equal to zero.

$$\Delta C_R = \sum_{i=1}^{3} C_i \left(\frac{m_i'}{m_i}\right)^{0.3} - \lambda\left(\ln R - \sum_{i=1}^{3} \left(\frac{t_i}{m_i'}\right)\right)$$

where the last term is the constraint imposed by equation 6-8

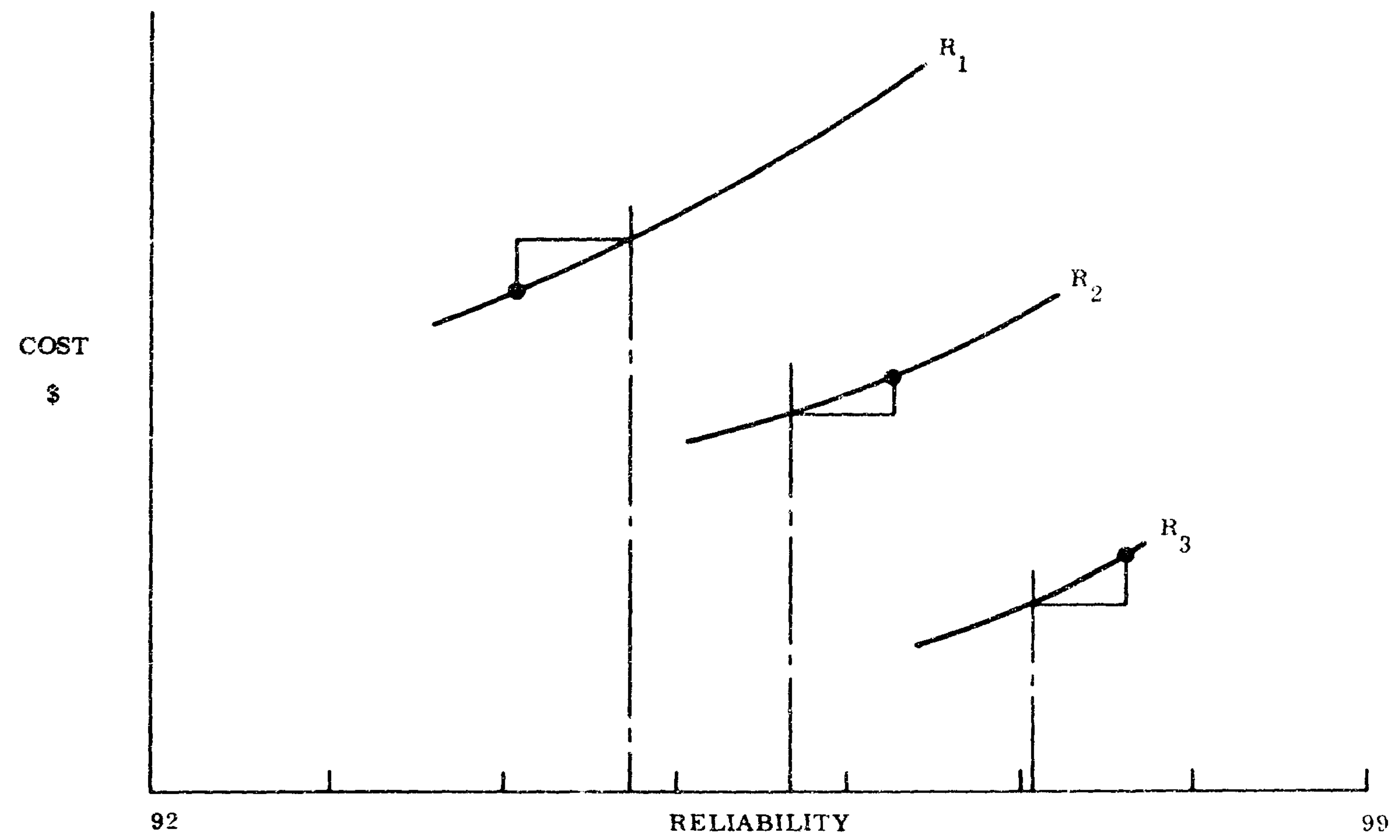
$$\frac{\partial(\Delta C_R)}{\partial m_i} = \frac{.2C_i}{m_i'} + \lambda \frac{t_i}{(m_i')^2} = 0 \text{ for each } i$$

$$\text{that is } \frac{t_i}{m_i'} = \frac{.2C_i}{\lambda}$$

This says that the ratios of the $\frac{t_i}{m_i}$ should be proportional to the C_i.

Since the C_i are related to the complexity by the ratio $N^{.88}$ (Equation 6-6) the optimum solution to the apportionment of reliability would be achieved by selecting as complexity factors the AEGs raised to the .88 power.

RELIABILITY COST TRADE OFF



Reference (8) provides a different correlation between initial cost and complexity to be used in case of developments in which performance involves design beyond the conventional state of the art, that is, for such cases

$$C = 1.464\ (29698)N^{.88}$$

In an apportionment, to account for the additional effort to achieve major advances in the state of the art in the design the complexity factor $N^{.88}$ should be multiplied by a factor of $\frac{1.464}{.891} = 1.644$.

Figure 6-20 gives an example of the application of this method. Subsystems C and E are assumed to require major advances beyond the present state of the art in development. Subsystems A, B and D are conventional design with minimum acceptable reliability requirements established somewhat beyond present normal achievements.

3. VOTING TECHNIQUES

In the early stages of development of a system, very little may be known about the hardware. Each of the techniques in paragraph 3 requires the application of more or less judgment in selecting some of the factors. If, as in the method covered in paragraph 2.3, the indices assigned are not representative of the ultimate equipment, the apportionment will create more problems than it will solve. Recognizing this, recent methods of apportionment attempt to limit the amount of judgment that must be applied. But no method can eliminate the requirement entirely. In conducting an apportionment, then, the task is to (a) select the method apparently most appropriate to the problem considering the details known, the nature of the equipment and the availability of pertinent data; (b) Identify the areas in which judgment is required, and (c) Arrange to obtain the best possible responses from qualified individuals.

3.1 FRAMING THE QUESTIONS

As was developed in paragraph 2, the apportionment depends on the selection of factors that are proportional to the number of failure to be "permitted" to the unit. These factors should be so selected as to minimize the difficulty of system development. That is a comparison must be made on (a) amount of development required for the unit; (b) complexity of the unit; (c) expected effect of the planned operational use on the difficulty in dev-

APPORTIONMENT CONSIDERING COST OF DEVELOPMENT

SYSTEM RELIABILITY REQUIREMENT

$R = \underline{0.90}$

SYSTEM OPERATING TIME 6 Hrs.

Subsystem	N(1)	t_i	$(N)^{0.88}$	f_i (2)	a_i (1)	R_i(1)	$(\frac{t_i}{m_i})$	m_i
A	40	6 hrs	25.7	25.7	.105	.9896	.0111	540
B	50	6 hrs	31.2	31.2	.127	.9867	.0134	450
C	120	6 hrs	67.6	111.2	.454	.9533	.0479	125
D	40	6 hrs	25.7	25.7	.105	.9896	.0111	540
E	50	6 hrs	31.2	51.2	.209	.9782	.0221	270

$$\sum f_i = 245$$

(1) N = active element groups (MIL-STD-756)

t_i = subsystem operating time

f_i = $(N)^{.88}$ for conventional systems

= $1.644\,(N)^{.88}$ for systems beyond the state of the art

$$a_i = \frac{f_i}{\sum f_i}$$

$$R_i = (R)^{a_i}$$

$$\frac{t_i}{m_i} = a_i\,(-\ln R) = 0.105\,a_i$$

$$m_i = \frac{1}{t_{i/m_i}} \times t_i = 9.52\,(\frac{t_i}{a_i}) = \frac{57.1}{a_i}$$

elopment; (d) the need for high unit reliability to achieve high system reliability.

Any general question posed to the judges such as "list these equipments in the ascending order of expected failure rates (or descending order of MTBF)" will not yield much valid information. Consider a more detailed set of questions, such as

> What is the level of vibration you expect this equipment to be subjected to?
>
> What level of vibration does equipment of this type normally withstand?
>
> Do you think this difference will cause you to have
>
> (a) fewer failures?
> (b) more failures?
> (c) no difference in the number of failures?

These latter questions forces the judge to concentrate upon one effect and provide his best judgment in an area in which he might feel confident.

The questions then, should be framed in a way to relate to the experience of the judge and should provide a suggestion as to how to go about arriving at a decision.

With a large number of interrelated factors, each factor must be given an appropriate weight. The difficulty of making a judgment involving many factors tends to make such judgments somewhat erratic and ineffective. In framing the questions, they should then be limited in the factors that are to be considered, and the factors should be within an area in which the judge feels competent.

3.2 SELECTING THE JUDGES

The less there is known about the unit, the greater is the importance of utilizing knowledge of engineers competent in the field. When a designer designs a new system he doesn't reinvent the components or the circuits. A bearing in a motor is the same as bearings in other motors. The new assembly has some innovations, but also it has many parts used in well known ways. Before the equipment is designed, a well qualified designer can tell you the characteristics of the parts he would use. He would know a great deal about the reliability of those parts.

In attempting to obtain an estimate or judgment on a particular factor, there is a real need to assure that the source is competent in the area of interest.

3.3 METHOD OF PAIRED COMPARISONS

3.3.1 Conducting the Survey: If the question to be resolved is very complex, such as the relative amount of development testing for the various units required to develop the system, it may not be possible for an engineer or a committee to set relative values. However, it should be possible for the engineer to make judgments of less complexity, say between two of them. A method due to Thurstone & Mosteller (5) has been devised to use such comparison of pairs to evolve a relative ranking of the item of interest.

Example: A new ship class is being developed, the major systems required for the "special" mission are:

- A. "Star Tracker" Navigation.
- B. "Ship to Space" UHF wide channel communications.
- C. "Lock-On" tracking system.
- D. Data acquisition and storage system.
- E. Computer analyzer.
- F. Data display system.

The item of interest is the relative cost of development of the subsystems. It was decided to obtain the judgments of eight engineers who had been working on radar, communications and computer complexes. The parameters of performance of each subsystem could be defined. The question was framed. "In the development of these two subsystems, E&F, say, which do you believe will require the most developmental testing to provide an operational system?"

Eight identical sets of cards were made, each set containing the comparison between each of the pairs of systems (AB, AC, BC etc.). Each engineer selected completed and returned his set.

3.3.2 Analysis of results:

(a) The individual cards were scored as follows. If the box marked "moderate" was checked, the card scored 1 "considerably more" was similarly counted 2. If the system first in alphabetical sequence was checked, the card was scored +, otherwise -. A sample card is shown in Figure 6-23.

SAMPLE CARD PAIRED COMPARISON METHOD

Card No. 12 | + | 2 |

1. In the development of systems

   C Lock-on tracking system — C ☑

   F Data display systems — F ☐

   which do you believe will require the most developmental testing to provide an operational system?

2. How much more developmental testing?

   About the same ☐

   Moderately more ☐

   Considerably more ☑

John Doe

Engineer

(b) The analysis was conducted in two ways. The averages of the car' were recorded in a matrix, Figure 6-25. It was noted that a definite order was indicated. C was felt to require more development than any other system, A next and the remainder following in the order B, E, F, D. These were replotted in matrix form, Figure 6-26.

Reasoning that the comparisons would be more meaningful between those considered close together the "strong" diagonal (C to A, A to B, B to E, etc.) was selected as the best relative comparison. Setting the one requiring the least development testing as the Standard, D=1. The relative scale of test requirements came out as follows:

System	Relative test requirements
D	1.00
F	1.125
E	2.000
B	2.250
A	3.000
C	3.125

An attempt was made to improve the analysis, using more of the information obtained, following the analysis described by reference 7.

Having the preference matrix the preferences were normalized using the equation $X_{.} = \frac{X+2}{4}$ (Figure 6-27).

The deviates were computed from the relationship

$$(X_n)_{ij} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{r_{ij}} e^{-X^2/2}\, dx$$

The deviate matrix is shown in figure 6-28. The deviates contained in the elements correspond to areas under the normal curve. The average of each row was computed and tabulated in the column r_i. The difference between the average deviates in each row were computed, using the relationship

$$r_i = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{T} e^{-X^2/2}\, dx$$

The values T then are used as proportional to the level of testing required in a program to develop the systems to an operational condition.

AVERAGE PREFERENCE MATRIX

	B	C	D	E	F
A	+1, 0, +1, 0 +2, +1, +1, 0 Ave: .750	-1, +1, +1, -1 +1, -1, 0, -1 Ave: -.125	+1, +2, +2, +2 +2, 0, +2, +1 Ave: 1.50	+1, +1, +2, +2 +2, 0, +1, +1 Ave: 1.250	+2, +1, +2, +1 +2, +2, +2, +2 Ave: 1.750
B		-2, 0, -1, -1 -1, -2, 0, -2 Ave: -1.125	+1, +2, +2, +2 0, -1, +2, +1 Ave: 1.125	0, +1, +1, 0 +1, -1, 0, 0 Ave: .250	+1, +1, -, +1 +2, +1, +2, +2 Ave: 1.250
C			+2, +2, +2, +2 +1, +1, +2, +2 Ave: 1.750	+2, +1, +1, +1 +1, +1, +2, +2 Ave: 1.375	+2, 0, +1, +2 +2, +2, +2, +2 Ave: 1.625
D				-1, -1, -1, -2 0, 0, -2, 0 Ave: -.875	0, -2, -1, -1 +1, +2, -1, +1 Ave: -.125
E					+1, 0, 0, +1 +1, +2, +1, +1 Ave: .875

PREFERENTIAL MATRIX

	C	A	B	E	F	D
C	0	.125	1.125	1.375	1.625	1.750
A		0	.750	1.250	1.750	1.500
B			0	.250	1.250	1.125
E				0	.875	.875
F					0	.125
D						0

NORMALIZED PREFERENCE MATRIX

	C	A	B	E	F	D
C	.500	.531	.781	.845	.905	.938
A	.469	.500	.686	.812	.938	.875
B	.219	.314	.500	.562	.812	.781
E	.155	.188	.438	.500	.718	.718
F	.095	.062	.188	.282	.500	.531
D	.062	.125	.219	.282	.469	.500

PREFERENCE RATINGS

	C	A	B	E	F	D	r_i	T
C	0	.08	.78	1.15	1.31	1.54	.810	.791
A	-.08	0	.48	.89	1.54	1.15	.663	.746
B	-.78	-.48	0	.16	.89	.78	.095	.538
E	-1.15	-.89	-.16	0	.58	.58	-.163	.434
F	-1.31	-1.54	-.89	-.58	.0	.08	-.706	.240
D	-1.54	-1.15	-.78	-.58	-.08	0	-.690	.245

4. USE OF APPORTIONMENT TECHNIQUES

4.1 CONCEPTUAL PHASE

Apportionment in the conceptual phase is primarily for determination of feasibility. The question that must be decided is the element of risk involved in undertaking the development. The apportionment assists in this determination by setting reliability goals against which to measure the capability of the industry. The AGREE method (paragraph 2.2) for electronics systems and the Boeing method (paragraph 2.3) for mechanical systems are appropriate. For electronics systems, the cost evaluation corrective factors may be applied (paragraph 2.5) to evaluate cost consequences.

4.2 PRELIMINARY DESIGN PHASE

In the early phases of design, the purposes for an apportionment are to provide requirements for supplier and contractor furnished systems, and to set targets (requirements) to be achieved in the design performed by the prime contractor -- or internally within the Bureau. The apportionment, to be comparable with design predictions, must be formulated on the same basis as the predictions will later be. It should include a comparable statement of environment and operating time. For electronics systems, the more detailed considerations of the Arinc method (paragraph 2.4) should be used. For mechanical systems, the Boeing method (paragraph 2.3) is the only useful method known. In attempting to use this system, the selection of weighting factors must be developed in such a way that they reflect the effect of the particular factor on the failure rate that will be achieved when the equipment becomes operational.

4.3 EVALUATION OF CONTRACTORS APPORTIONMENT

When contractors perform an apportionment to allocate a system requirements to units, the Bureau engineer responsible must evaluate his apportionment process to assure that the unit requirements are based on a sound appraisal of cost and effectiveness. The techniques in paragraph 2.0 demonstrate the methods most likely to be used. Where some other method is used, the basis of the method should be evaluated against the criteria (equation 6-4 and paragraph 1.2).

4.4 SUMMARY

In summary, reliability apportionments are made:

(a) To set reliability requirements for units of a system to establish procurement and/or design objectives.

(b) To provide a means of measuring progress toward achievement of the system reliability objective.

The value of the apportionment in achieving these objectives depends on the care and judgment used in making the apportionment.

Since the apportionment is used primarily as a guide to the achievement of the system objective it should be continuously updated as the design progresses and used to modify the requirements imposed on the component suppliers and subsystem designers as more information becomes available. Apportionment should be continuously used as a tool to achieve the system objective.

5. REFERENCES

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(3) The Allocation of System Reliability, Tech. Documentary Report No. ASD-TDR-62-20, June 1962 (AD282272).

(4) Reliability Control in Aerospace Equipment Development, Society of Automotive Engineers, Technical Progress Series, Vol. 4.

(5) Remarks on the Method of Paired Comparisons, Psychometrica, Vol. 16, #1, March 1951.

(6) Advanced Theory of Statistics, M. G. Kendall, Vol. 1, p. 421.

(7) Saturn Stage S-II, Reliability Apportionment Report, North American Aviation, Report SID62-1225, 17 October 1962.

(8) Cost and Time Factors Relating to Reliability in Development Planning, Bird Engineering Research Corporation, Final Report under Contract NOW-62-0990-C.

(9) A Procedure for Estimating Cost, Time and Reliability in Development Planning, Bird Engineering Research Associates, Inc., Report on Contract NOW-62-0990C.

Chapter 7

STRESS-STRENGTH ANALYSIS

CHAPTER 7

STRESS-STRENGTH ANALYSIS

The concept of safety margins (1) has been developed from the traditional safety factor of the structural design disciplines. Safety factors in design have long been used with a high degree of success based on knowledge evaluated from successful applications, simple testing, or proofing. They are predominately empirical in nature and are usually intuitive, based on engineering judgment. Safety factors are traditionally generous and may often cause weight and cost penalties which cannot be tolerated. Safety margins are essentially modified safety factors and are derived from comparing a distribution of possible loads to a distribution of possible resistive strengths.

No two things can be identical; they are inherently variable to some degree. The variation in material from lot to lot and from producer to producer is well known. The variation in loads from experiment to experiment and between periods or cycles of use can equally be established. As discussed in Chapter 9, stresses and loads can be described by distribution functions in which the frequency of occurrence of stresses or strengths is compared to the stresses or strengths occurring.

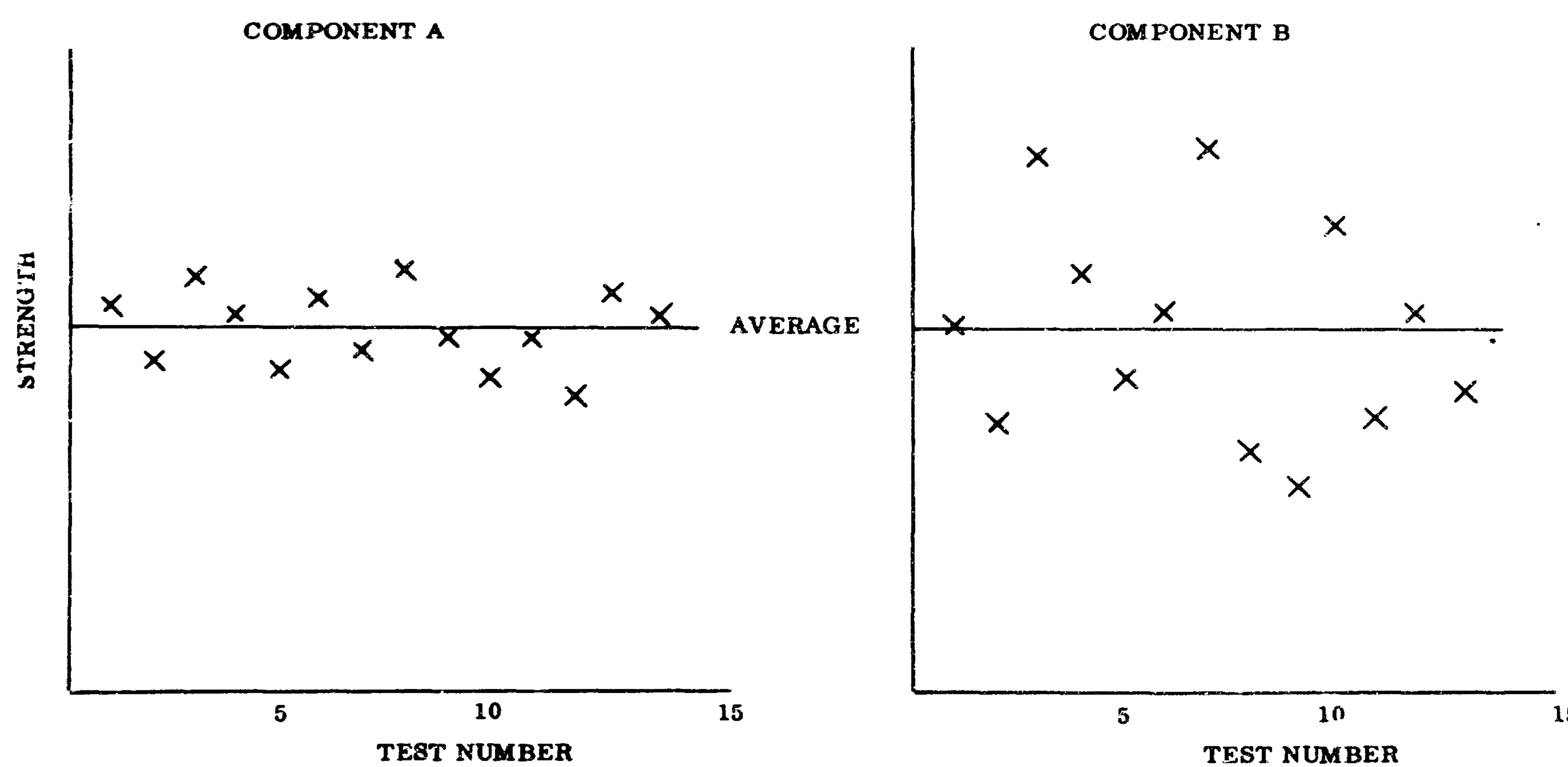
The concept is not limited to the structural field. The generalization of the stress-strength analysis to electric, hydraulic or mechanical equipment is obvious wherever a (generalized) stress exceeds the strength of the material to resist a failure result. If the stresses and strengths vary in an identifiable fashion,* the frequency with which failures can be expected to occur can be computed by the stress-strength technique.

1. THE PRINCIPLE OF SAFETY MARGINS

It would be ideal to have specifications which would increase both reliability and performance. We may come closer to achieving this goal by replacing the principle of rigidly specified safety factors by the more effective principle of safety margins to take account of the fact that unreliability is caused not only by low averages but also by large variations of strength.

Variations may be large or small, as illustrated in Figure 7-3. Although components A and B have the same average strength, component B evidently is less consistent than component A. It is, therefore, imperative that the characteristic variation of stresses and strengths be determined also, by testing sufficient

COMPONENT STRENGTH VARIATION



samples to failure. The result of such a test-to-failure program is illustrated in Figure 7-5.

The reader will note that on test number 7 the component is weaker than the stress to which it will be subjected, and therefore will fail.

Obviously, scatterbands of stresses and strengths must be separated by safety margins. Here the question arises how large the safety margins should be to achieve the required degree of component reliability.

Before we may discuss this vital question, we must dwell for the moment on the widespread misconception that reliability may be judged on the basis of a single failure test.

Figure 7-5 indicates that safety factors fluctuate even more violently than the stresses and strengths upon which they are based (compare tests No. 5 and 6). Therefore, relying on the test-to-failure data of just one unit is shortsighted and irresponsible. This is illustrated in Figure 7-6 where the scatterband of stress data has been replaced by the maximum stress level, called the "Reliability Boundary".

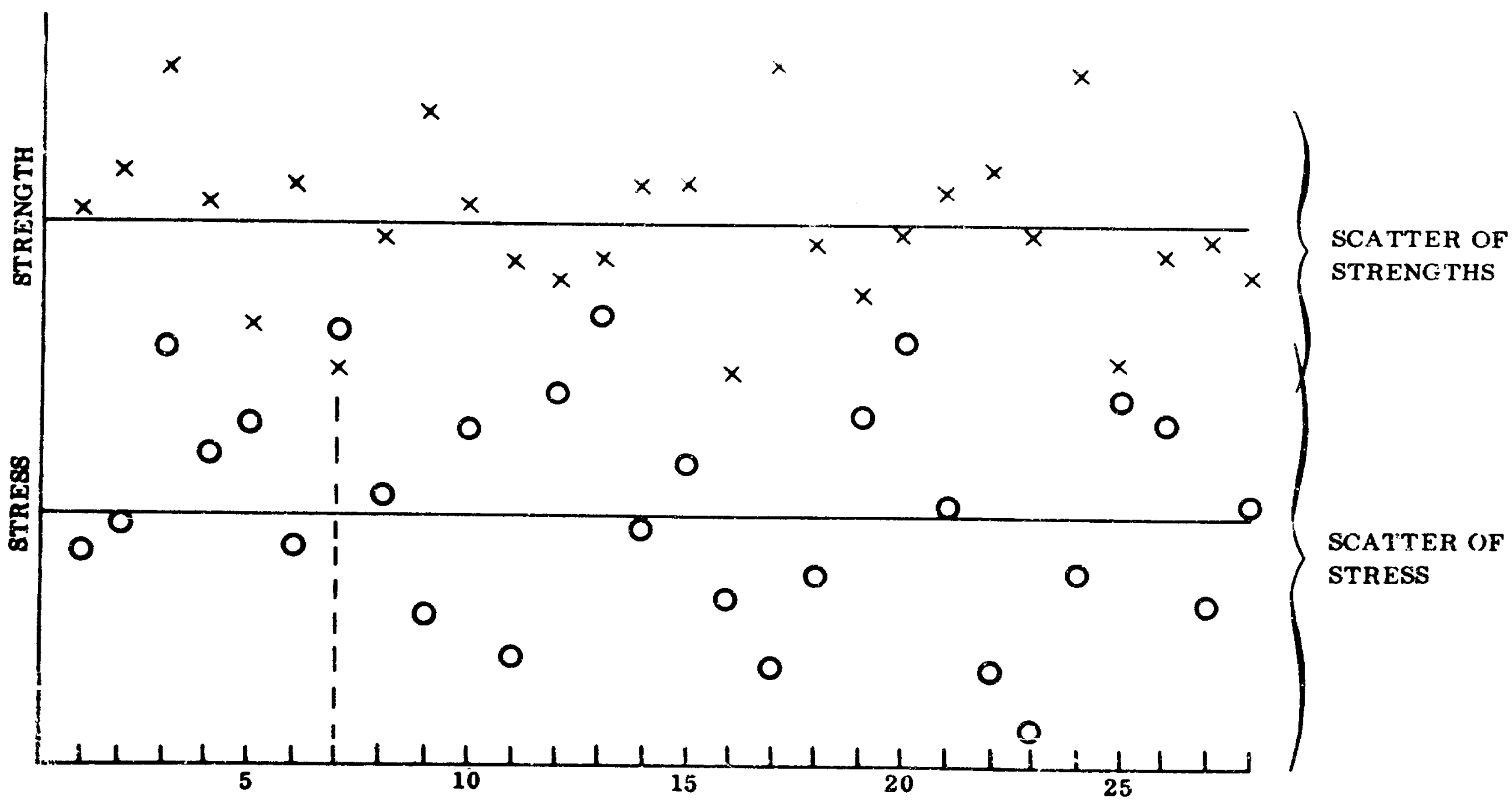
If only one test were conducted and relied upon, and if the result complied with the specified minimum safety factor of 1.5, as illustrated by the dot, (T), the component type might be accepted for mass production and employment in complex military equipment. If, however, more units were tested to failure, a shocking degree of variation, hence unreliability, would be revealed.

1.1 HOW TO JUDGE AND INCREASE SAFETY MARGINS

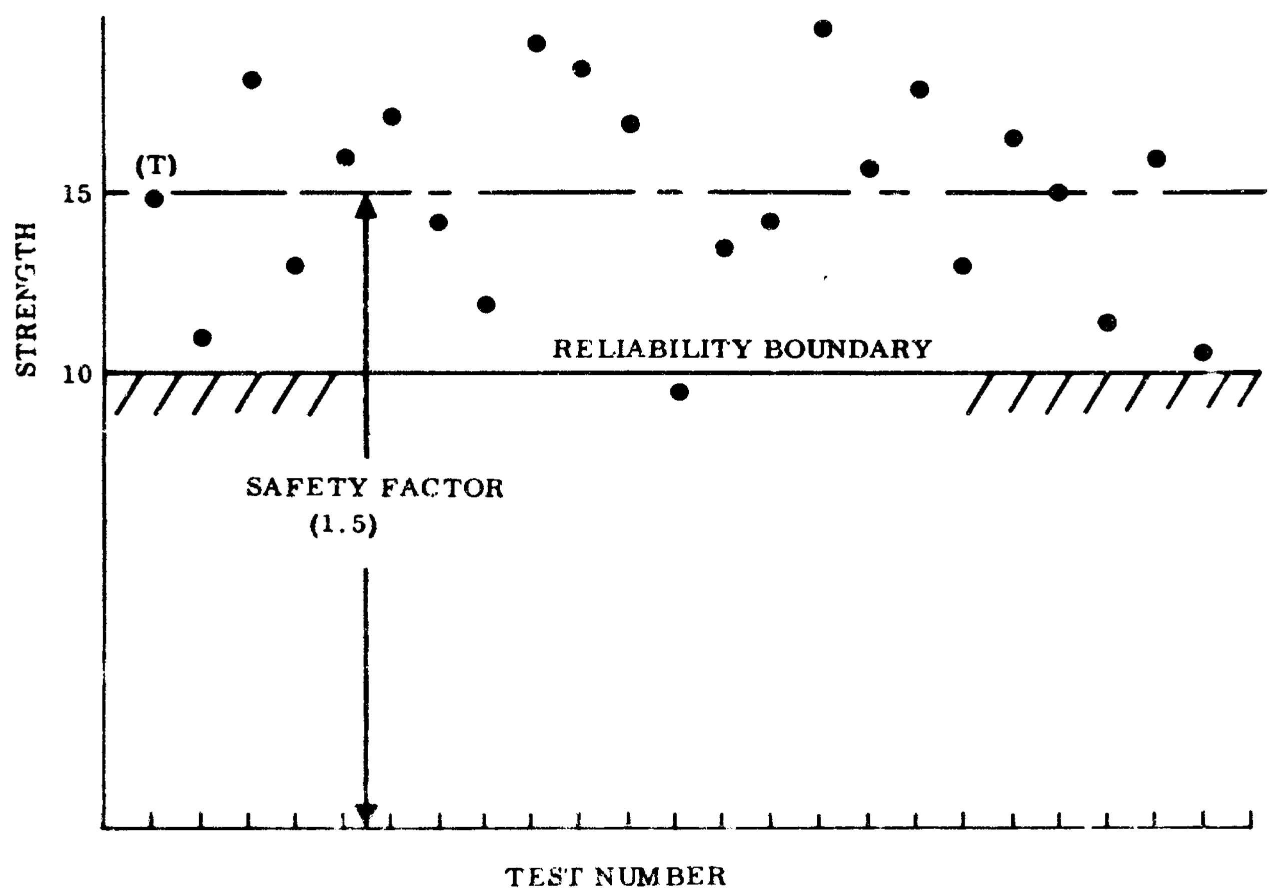
The principle of safety margins is illustrated by the examples shown in Figure 7-7.

Let us assume that between the average strength and the Reliability Boundary a minimum safety margin of five standard deviations were specified. After having tested a sample, say 12 units, to failure we compute the standard deviation and find that the safety margin is only 2.7 standard deviations (Figure A). Thus, the safety margin must be increased. We may first try to lower the severity of the environmental condition, for example by providing a shock absorber or by intensifying the cooling of the component. If neither is practical, the component must be redesigned. In most instances, this is made easier by the fact that

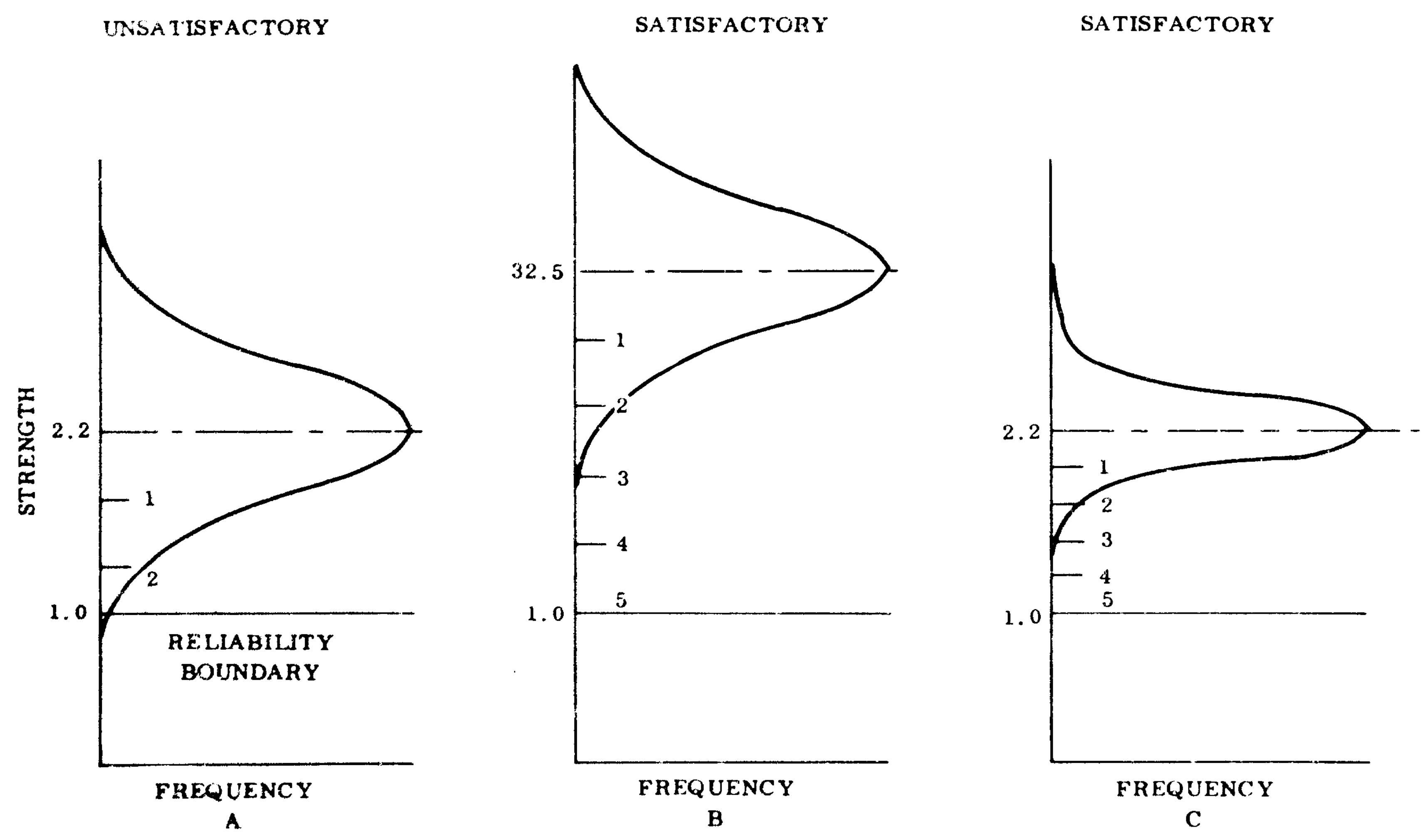
STRESS AND STRENGTH SCATTERBANDS



SINGLE UNIT TESTING FALLACY



DEVELOPING A RELIABLE PART



the failure tests will have revealed the prevailing modes, or mechanisms, of failures. Either the average strength may be increased, as shown in Figure B, or the inherent variation reduced, as in Figure C, whichever appears most suitable to save weight, time, or expense.

Components having very large safety margins may be considered "absolutely" reliable. They may be placed in the "'good' basket", thereby freeing us to concentrate on those component types which still suffer from low safety margins.

When saving of weight is of prime importance, as in the design of structural components, the concept of safety margins permits saving weight by keeping the safety margin down to the specified minimum of, say five standard deviations. In the design of simple structural parts having very small inherent variations of strength, such as machined pins, the designer may reduce dimensions and weight to a bare minimum if he can prove, through tests to failure, that the specified minimum safety margin of, say five standard deviations, is still available.

It thus becomes evident that the principle of safety margins not only helps to achieve and control the required "absolute" degree of component reliability, but also helps to improve performance by indicating where dead weight may be saved. Thus the crucial antagonism between performance and reliability may be greatly alleviated.

7.2 HOW MANY STANDARD DEVIATIONS?

The question arises: How many standard deviations shall be specified? Actually, there is no fixed number to be specified for all types of components, relative to all environmental conditions and design criteria for the following reason: to assure that a component type will never cause the loss of complex military equipment, every conceivable risk factors, such as uncertainties of measurements, skills, and of war conditions, must be considered. Specifying and attaining the minimum contingency margin is the responsibility of the engineer.

Once a satisfactory degree of design reliability is established, and proved to exist by tests to failure, the quality control engineer will take over. He has the responsibility of assuring, by approved methods of statistical quality control, that during the manufacturing process neither the average strength decreases nor the standard deviation increases. He must prove this continuously by testing to failure small but adequate production samples with regard to those environmental conditions which, during the prototype tests, have shown the need of permanent control. In this manner, the quality control engineer may maintain, and even increase, the safety margins established in the prototype stage.

Considering only the variations in strength (Figure 7-10) compared to a reliability boundary. A limit may be determined, from the frequency distribution, below which the strength will be found any given fraction of trials. (The 3 sigma rule, when the normal distribution applies, is an example of this. The actual value will be found below 3 standard deviations below the mean only .00135 of the time). As the figure shows, a contingency margin should be provided, in addition to the computed scatter margin to provide for unverified assumptions. Figure 7-11 provides the complete picture. Stress is controlled to keep a safety margin between the design minimum (probable) strength and the design maximum (probable) stress.

1.3 OVERDESIGN AND RELIABILITY

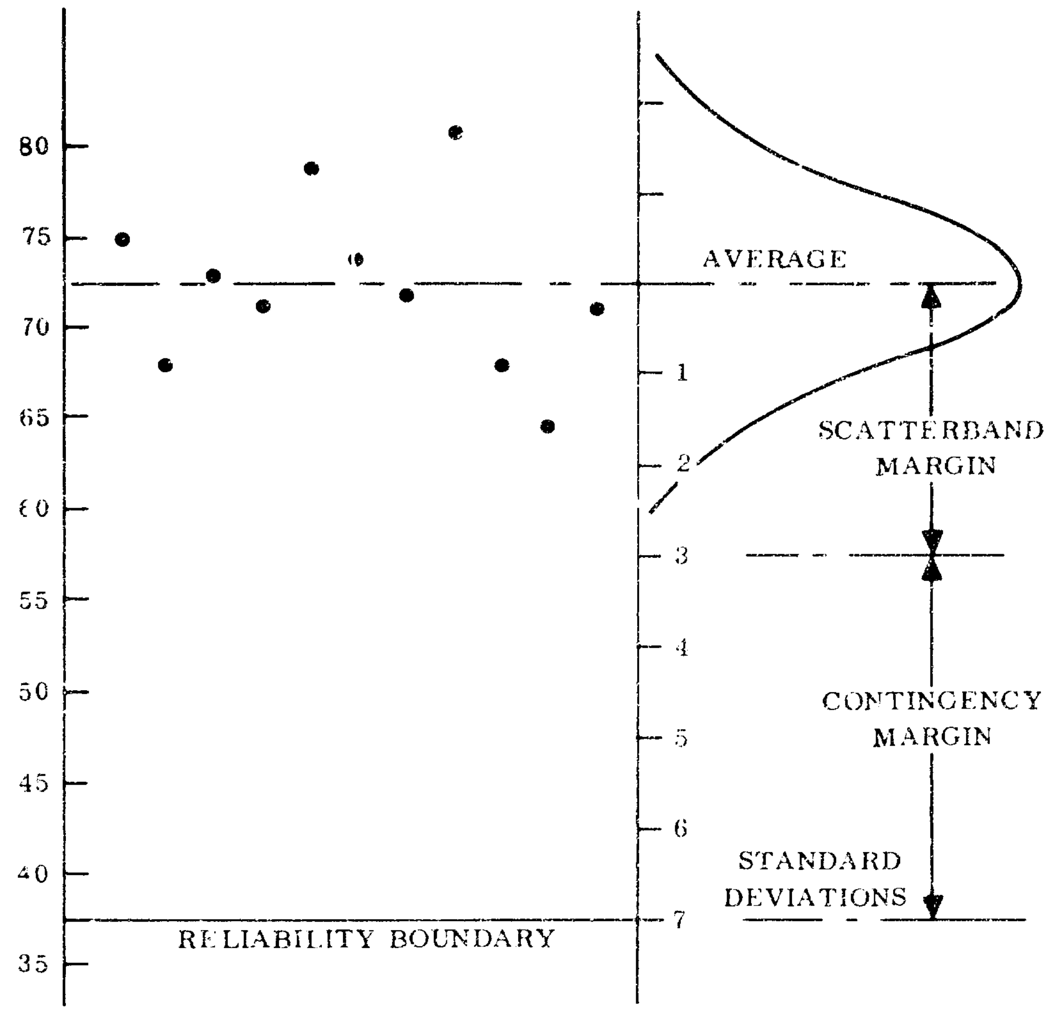
It is often argued that generous safety margins unavoidably lead to overdesign, that is, to excessive weight, reduced performance, high cost, and delayed schedules. Is this true?

There is the performance fanatic who, by sacrificing reliability, economy and schedules, tries to squeeze out of his design the ultimate degree of performance, the maximum output. There is the unresourceful, apprehensive designer who clings to his design, unable to finish and release it for production. In either case, warnings against overdesign are well justified.

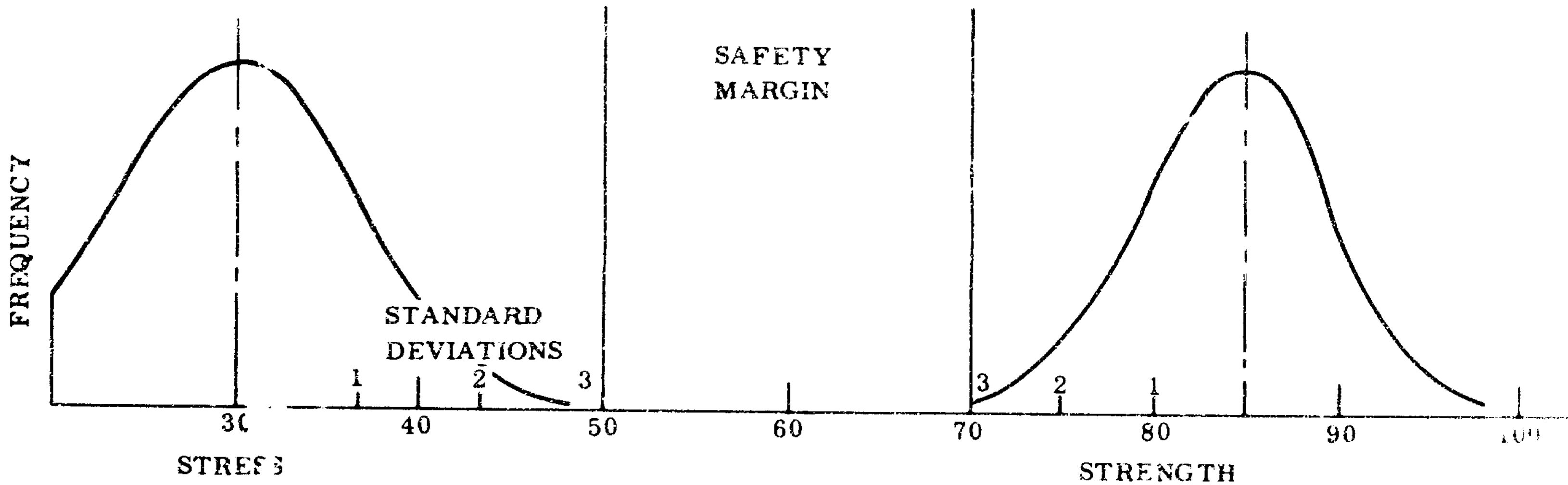
But there is also the hasty, superficial designer who, pretending to fight against overdesign, tries to push a new design into production, be it mature or immature, light or heavy, inexpensive or expensive, reliable or unreliable.

Significantly, advocates of haste and superficiality are the ones who assert that reliability may be improved later, during production and service use, by quality control and failure reporting. Since this is impossible, they just bring about the very consequences of overdesign they pretend to battle, namely excessive weight, reduced performance, high cost and -- as a result of necessary design changes -- badly delayed schedules. Worst of all, they bring about poor reliability.

SCATTER & CONTINGENCY MARGINS



STRESS/STRENGTH SAFETY MARGIN



While warnings against overdesign are oftentimes justified, they must never be misconstrued as an invitation to neglect the principle of safety margins. Whenever this is the case, the engineer must take immediate action, education or otherwise, before a low reliability barrier becomes chronic and incurable.

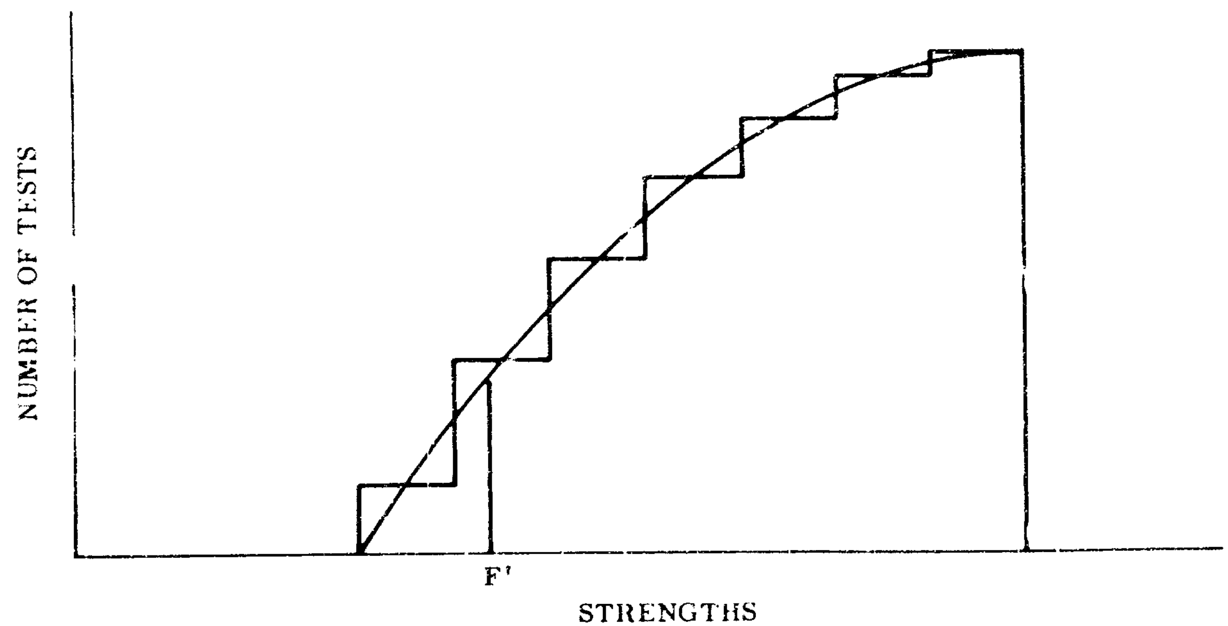
2. STRESS AND STRENGTH DISTRIBUTIONS

For the purpose of discussing the concepts of stress-strength analysis, we have used a normal distribution in our examples. The assumption that stresses and strengths are normally distributed is not necessarily valid. In using the stress-strength approach, this assumption is dangerous (much more than in estimating mean time between failures, for example) because the comparison is being made well out on the tail, in the extreme value region. Other possible distributions, approximating the normal, such as Poisson, Gamma, Weibull, or distributions like the log-normal, are also eligible candidates. The identification and testing of distributions is covered in chapter 10. We will discuss a generalized distribution here to guide the use of probability theory to the establishment of safety margins.

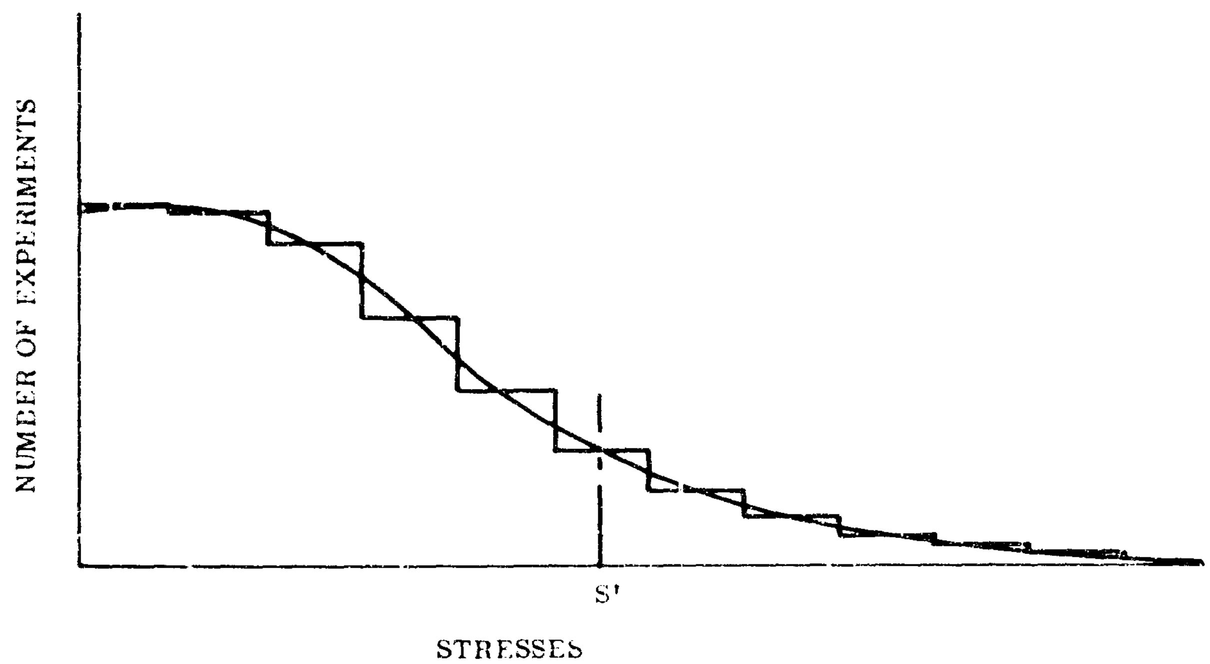
2.1 JOINT DISTRIBUTIONS

If you assume a large number of tests of the strength of a given manufactured part, each test being run to failure, some relationship between the number failing at any particular value of strength (or band of values) and the value can be determined. This is called a frequency distribution or density function (Figure 7-13). If the exact relationship were known, you could predict the probability of a randomly selected specimen failing at a particular value of stress F'. It would be that fraction of the population, whose strength was equal to or less than a stress F'. Similarly, if you conducted an experiment a large number of times, recording the stress on each experiment, a relationship between the relative frequency (or density) of stresses and the stress could be established. If the exact relationship were known, you could predict the probability that on any randomly selected trial (Figure 7-14) the stress would exceed a strength S'. This would be the fraction of the population (of possible trials) in which the stress exceeded the strength S'. These fractions are, of course, the ratio of the areas under the curve to the left of F' or right of S' to the total area under each respective curve. If the two curves are "normalized", that is if the ordinates on the curve are divided by a common factor such that the total area under the curve is

STRENGTH FREQUENCY DISTRIBUTION



STRESS FREQUENCY DISTRIBUTION



equal to 1.0, then the areas under the tails are the probabilities of failure.

Looking at Figure 7-16, the probability that the strength will be S on a particular part is the area under the curve F(S)dx. The probability that the stress, F, is equal to or greater than the strength, S, on any particular experiment is the area under the tail

$$\int_S^{\infty} F(F)\,dF$$

The probability that a failure will occur is the probability that S = x and F > x. This is the product of the individual probabilities. So the probability that a failure will occur (Q) is

$$Q = \int_{-\infty}^{\infty} F(S) \left[\int_x^{\infty} F(F)\,dF \right] dx$$

This equation can be solved analytically, graphically, by numerical integration or by probabilistic techniques such as "Monte Carlo" provided the form or shape of the probability distribution functions F(S) and F(F) can be determined (chapter 10).

2.2 STRESS-STRENGTH ANALYSIS FOR THE NORMAL DISTRIBUTION

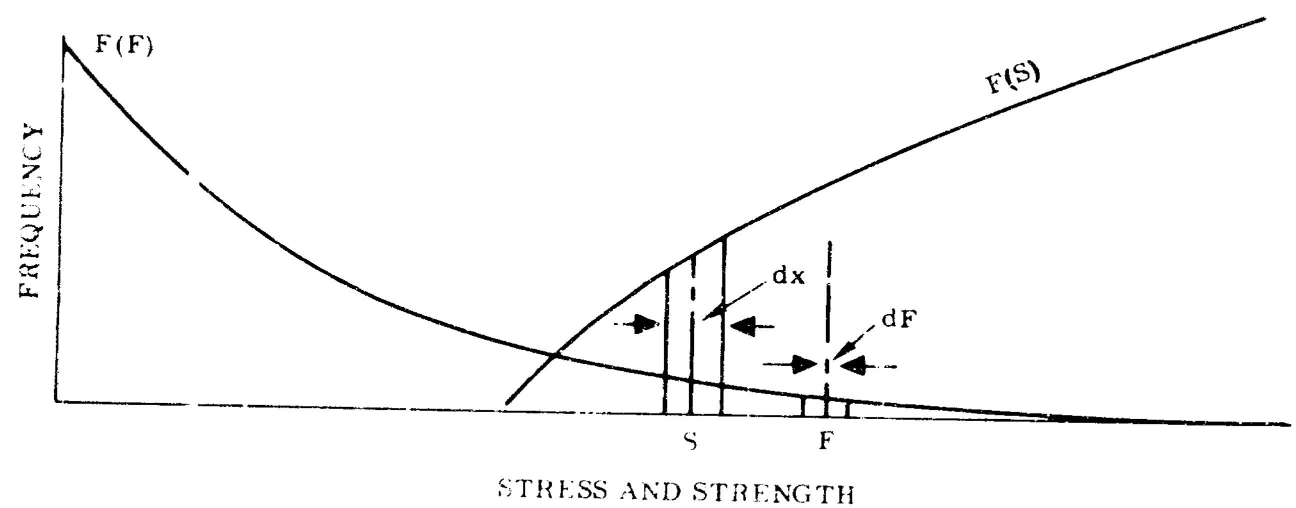
2.2.1 Analytical Basis: If both distributions are Normal (gaussian) an analytical solution has been developed. Letting $\bar{S}$ be the mean value of the strength with standard deviation s and $\bar{F}$ be the mean value of stress, with f its standard deviation then the probability distributions of S and F are

$$F(S) = \frac{1}{\sqrt{2\pi}\, s} e^{-\frac{1}{2}\left(\frac{S - \bar{S}}{s}\right)^2}$$

$$F(F) = \frac{1}{\sqrt{2\pi}\, f} e^{-\frac{1}{2}\left(\frac{F - \bar{F}}{f}\right)^2}$$

If we designate D = S - F then the reliability (the probability that S > F) can be determined from the equation D = S - F >0. F(D) is defined as the difference distribution of F(S) and F(F). F(D) is also normally distributed (3).

PROBABILITY OF STRESS EXCEEDING STRENGTH



$$F(D) = \frac{1}{\sqrt{2\pi}\, d} e^{-\frac{1}{2}\left(\frac{D - \bar{D}}{d}\right)^2}$$

where $\bar{D} = \bar{S} - \bar{F}$ and

$$d = \sqrt{s^2 + f^2}$$

The reliability is given by

$$R = P(D > 0) = \frac{1}{\sqrt{2\pi}\, d} \int_{0}^{\infty} e^{-\frac{1}{2}\left(\frac{D - \bar{D}}{d}\right)^2}$$

If we set $Z = \dfrac{D - \bar{D}}{d}$, then

$$R = \frac{1}{\sqrt{2\pi}} \int_{-\left(\frac{\bar{D}}{d}\right)}^{\infty} e^{-\frac{Z^2}{2}}\, dZ$$

2.2.2 Application: The method basically involves the steps outlined in Figure 7-18 and discussed herewith:

A. Determine Approximate Design: Since the method involves prediction of reliability from geometry of the design, a tentative configuration must be established. As the analysis progresses, the design is corrected and refined to satisfy the criteria.

B. Determine Critical Stresses: Since all stresses in a design do not lead to failure, we must first select and quantify those stresses that will cause failure if they exceed achievable strength. The word "critical" is used to denote these. The following steps are involved:

1. Determine the nominal stresses, each as a function of loads (normal and shear), temperature, geometry, physical properties (Poisson's ratio, Young's modulus, shear

DESIGN TO RELIABILITY MARGIN

A. <u>DETERMINE APPROXIMATE DESIGN</u>

B. <u>DETERMINE CRITICAL STRESSES</u>
   1. Determine the nominal stresses
   2. Determine factors affecting maximum stress
   3. Calculate all critical stress components
   4. Calculate critical mean stresses
   5. Determine critical stress distributions for useful lifetime

C. <u>DETERMINE MATERIAL AND ITS UNIT STRENGTHS</u>
   1. Determine all critical unit strength mean values
   2. Determine factors that affect strength
   3. Determine actual unit strength means and distributions

D. <u>DETERMINE REQUIRED STRENGTHS</u>
   1. Translate reliability requirement to Reliability Margin
   2. Calculate mean stress/strength variances
   3. Calculate required mean strengths

E. <u>DETERMINE SIZE AND SHAPE</u>
   1. Select or design for section modulus required
   2. Modify design and/or material until achieved

F. <u>VERIFY DESIGN RELIABILITY MARGIN</u>
   1. Conduct independent Reliability Margin analysis
   2. Conduct tests to failure for critical margins
   3. Modify design and/or material until verified

modulus, thermal expansion, thermal conductivity) and time (stress cycles vs. life).

2. Determine factors affecting maximum stress such as (5): (a) stress concentration factors (b) load factors such as static, dynamic, impact, shock, and energy, (c) temperature stress factors around critical points, (d) manufacturing stress factors such as for machining, grinding, extruding, and drawing, (e) surface treatment stress factors such as for shot peening, cold working, and plating, (f) heat treatment stress factors via distortion, (g) assembly stress factors such as for shrink and press fits, (h) notch sensitivity factors, particularly in fatigue, (i) environmental stress factors such as surface corrosion and gross temperature effects. When these are appropriately combined with the basic nominal stress, the effect, as shown in Figure 7-20, is to establish a higher critical mean stress.

3. Calculate all critical stress components: First determine which of the stresses, considering the above factors, are likely to be critical (i.e. approach strength and cause failure if they do). Then for each calculate all three normal and all three shear stresses, while the appropriate stress factors are applied.

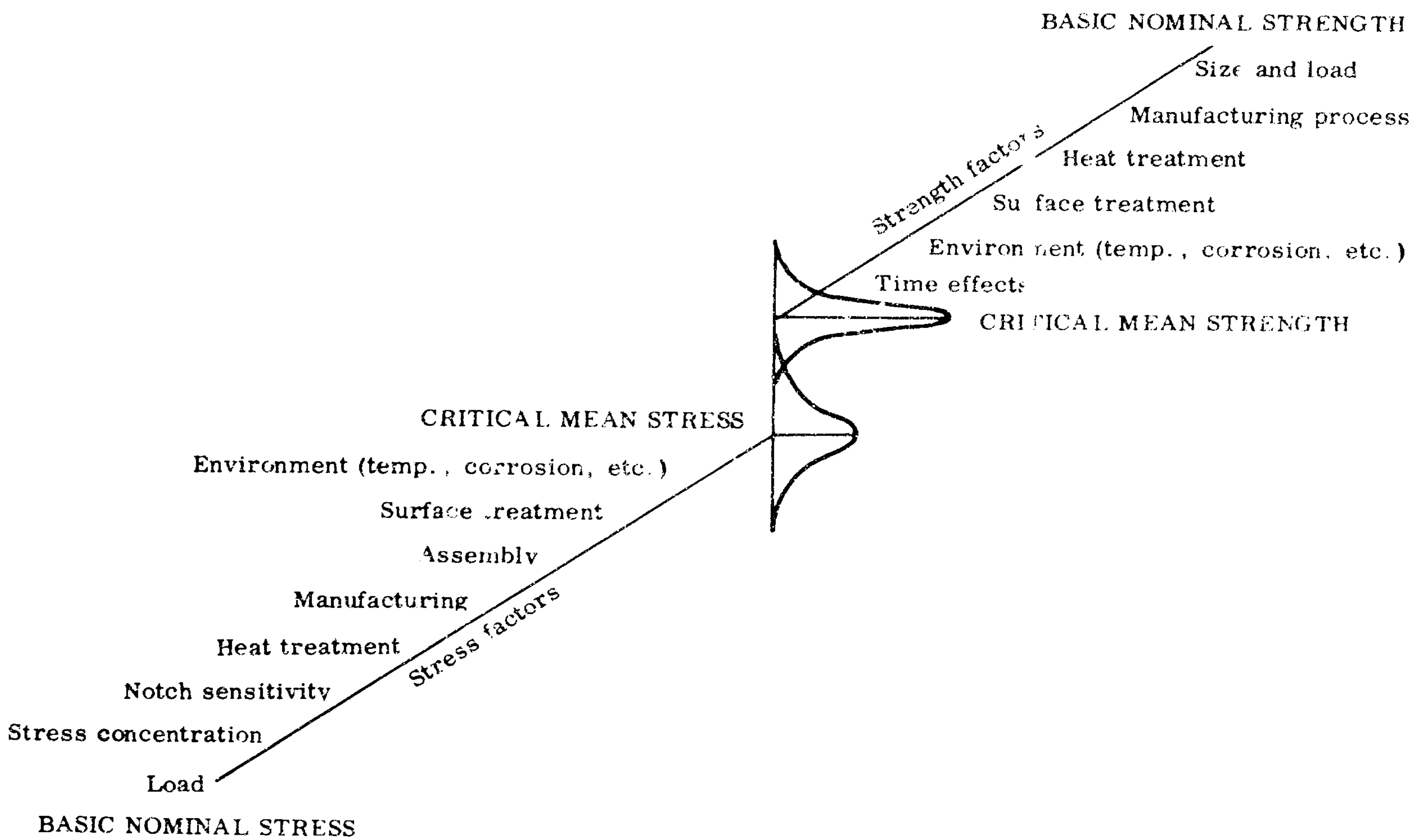
4. Calculate critical mean stresses, such as maximum tensile stress, shear stress, or distortion energy, or the combination of mean and alternating fatigue stresses.

5. Determine critical stress distributions for useful lifetime. This can be done by listing all the principal application situations, the environment for each, the resultant critical stress for each, and the estimated per cent of lifetime that it will encounter each situation. Then a normal (or other) density function can be fitted to the data by regression, and (if normal) the standard deviation obtained.

C. Determine Material and its Unit Strength. Here much depends upon the criterion for strength beyond which failure is defined to have occurred:

1. Determine all critical unit strength mean values: Select one or more suitable materials. Then determine (a) direct stress/strain criteria (ultimate strength, yield strength, or proportional limit, depending upon application).

STRESS & STRENGTH FACTORS



(b) shear strength in the same way, (c) distortion energy strength, and (d) fatigue strength.

2. Determine factors that affect strength, such as (a) size and load, (b) manufacturing processes, (c) heat treatment, (d) surface treatment, (e) environment (temperature, humidity, corrosion, etc.), and (f) time effects (aging, cold flow, fatigue, and corrosion). Figure 7-19 shows the general strength reduction due to these factors.

3. Determine actual unit strength means and distributions. Apply the appropriate strength factors to determine the net mean strength for the application conditions. Then determine the distribution for each from the material suppliers or testing laboratories, or conduct tests-to-failure as necessary. Again fit a normal (or other) density function to the data by regression, and (if normal) obtain the standard deviation.

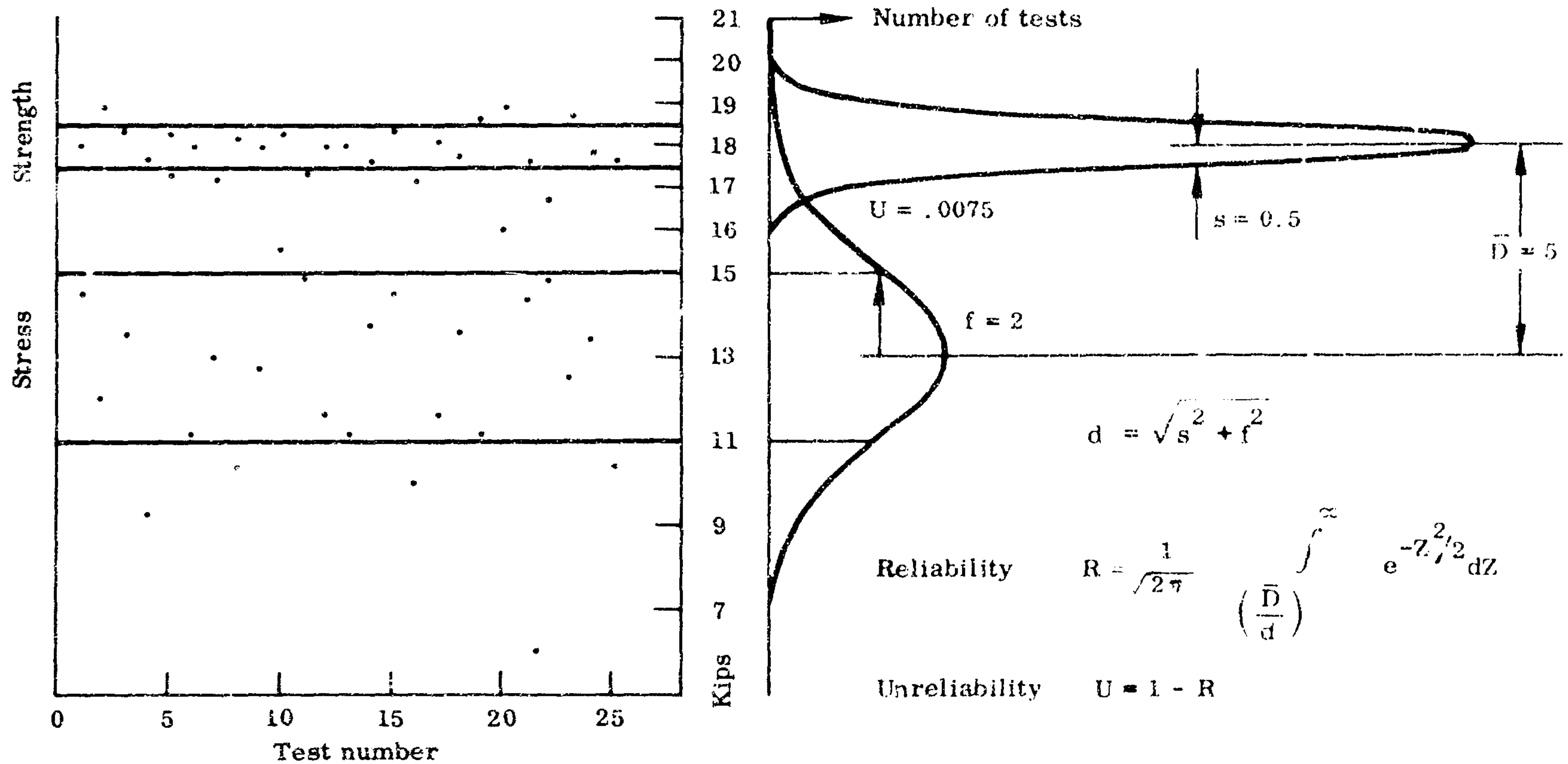
D. Determine the Required Strengths: Now that we have the anticipated stresses and the material unit strengths, we can proceed to determine the total strengths required for adequate reliability. But first let's examine the stress/strength relationship.

If we were to conduct a series of 25 tests of a critical stress within a given design, they might fall in a "scatterband" as shown in Figure 7-22. If these stress points are "normally" distributed, 68% will fall within a band of say ± 2 kips each side of the example mean 13 kips, another 27% will fall within the next 2-kip bands on each side, another 4% in the next 2-kip bands, etc. This is expressed by the area under the standard density function curve at the right. The "standard deviation" of this normal distribution is f = 2 kips.

Now if we were to conduct a similar series of tests-to-failure to get strength of the material, we typically would find the same shape of curve, but some other value of standard deviation. For the example it is s = 0.5 kip. And we now see that the mean values are separated by D = 5 kips.

Now the overlap of the two curves tells us that if we were to conduct enough tests, or encounter enough operational situations, sooner or later we will get a stress point exceeding strength, and we should have a failure. The probability that this will not occur, for normal distributions, as we have seen

NORMAL STRESS/STRENGTH DISTRIBUTION



$d = \sqrt{s^2 + f^2}$

Reliability $R = \frac{1}{\sqrt{2\pi}} \int_{\left(\frac{\bar{D}}{d}\right)}^{\infty} e^{-Z^2/2} dZ$

Unreliability $U = 1 - R$

$$\text{Reliability } R = \frac{1}{\sqrt{2\pi}} \int_{-\left(\frac{\bar{D}}{d}\right)}^{\infty} e^{-\frac{Z^2}{2}} dz$$

which is the area under the normal density function, available in many books (7) to

$$\left(\frac{\bar{D}}{d}\right) = 3.5.$$

Extensions to

$$\left(\frac{\bar{D}}{d}\right) = 8.4$$

can be obtained from references (8) using

$$x = \left(\frac{\bar{D}}{d}\right)/\sqrt{2} \quad \text{and } R = 1 - (1\text{-area})/2,$$

Since R provides an unwieldy string of 9s, it is usually more convenient to express Unreliability $U = 1 - R$. $\bar{D}$ is the difference between mean strength and stress, and s and f are the respective standard deviations. Figure 7-23 gives the resultant relation of U to $\left(\frac{\bar{D}}{d}\right)$. With this background we can outline the procedure:

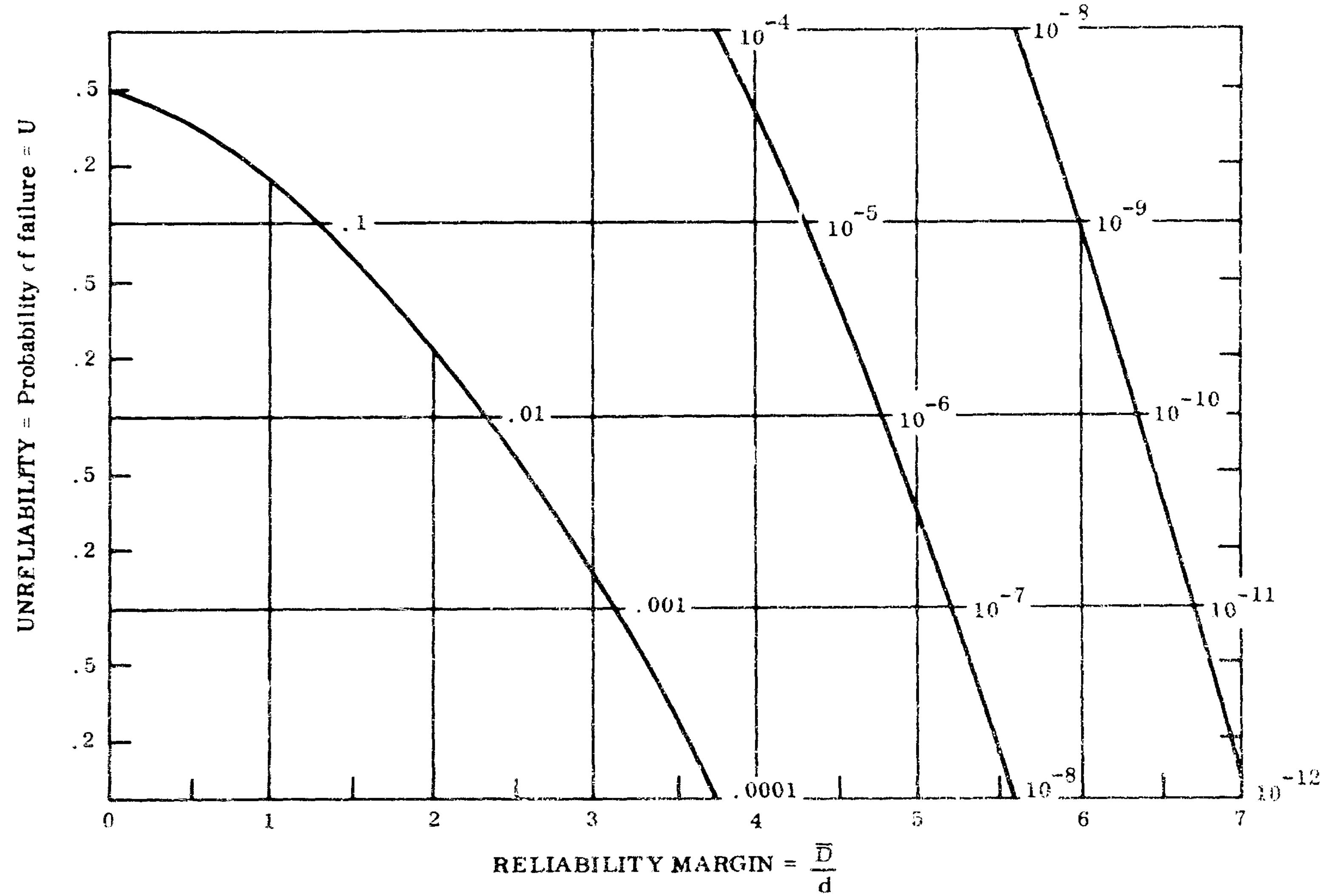
1. Translate reliability requirement to Reliability Margin: Calculate U from the specified reliability $R = 1 - U$. Use Figure 7-21 to find the required Reliability Margin $\left(\frac{\bar{D}}{d}\right)$.

2. Calculate mean stress/strength variance: Use the standard deviations s and f obtained from B5 and C2 above, to obtain their mean $d = \sqrt{s^2 + f^2}$.

3. Calculate the required mean strengths, by adding $D = \left(\frac{\bar{D}}{d}\right) \cdot d$ to mean stress. Now we know what strength is needed to achieve the required reliability.

E. Determine Size and Shape: Now that the material and its unit strengths have been established, and the required strengths calculated, we can proceed to design for adequate size and shape to

RELIABILITY MARGIN



achieve the required strengths:

1. Select or design for the section modulus required, using standard section handbooks and established design calculations.

2. Modify the design and/or the materials until all Reliability Margins are met.

F. Verify the Design Reliability Margin: Nearly all design involves many assumptions to avoid unjustifiable volume of analysis or test cost. The above approach permits design to predictable reliability, but does not insure against design errors of assumption, analysis, omission, etc. Verification is covered in chapter 13.

2.2.3 Other Distribution: The preceding approach assumed that both stress and strength distributions were normally distributed, that is, could be described by the normal (gaussian) distribution. As mentioned earlier, this is a very dangerous assumption. Where a distribution can be established, analytical solutions can be derived. Reference (5) provides a very useful listing of references for special distributions.

The computation of the difference functions and the determinations of reliability have been analytically established for the log normal (4), Gamma (5) and Weibull (6) distributions. Reference 5 also suggests alternatives such as conformal mapping or numerical or graphical integration for obtaining solutions in special cases.

2.2.4 Stress/strength testing: When distribution data is not obtainable for the above analytical approach, yet the design reliability is a critical matter, it may be necessary to conduct experimental tests. Tests to determine stress distribution in a prototype are fairly straightforward and non-destructive, using instrumentation such as strain gages, plastic models and polarized light, etc. To the extent that such tests can simulate the manufacturing variances, operational environment, external stresses, and time effects, the results can be quite dependable.

But tests of strength distribution are much more difficult, expensive, and time consuming. If the design engineer can identify specific local areas of critical doubt, a series of comparatively simple tests can be designed, wherein stress is repeatedly increased until failure occurs, providing a rough strength distribution curve for the local area. On the other hand it may be more convincing, if not more economical to test an entire prototype in the same manner, so that all interactions are accounted for, repairing failures each time they occur. Of course as strength inadequacies are thus brought to light, the design is changed to get required strength.

Such stress/strength testing should not be confused with simple "overstress" testing, which determines only that the design does not fail at some specified stress above the operational level. Over-stress testing does not generally determine strength.

3. APPLICATIONS

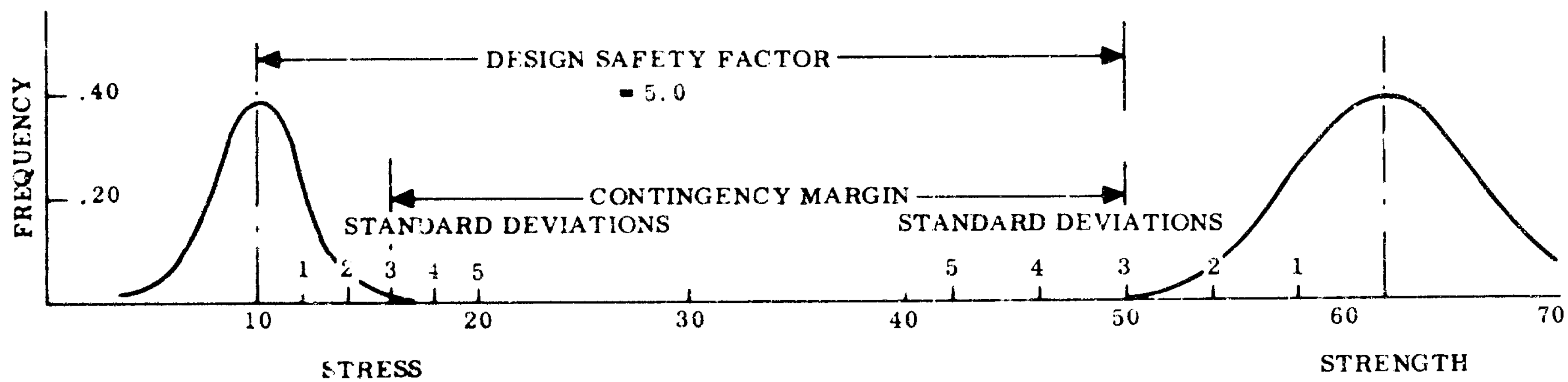
The use of the "safety margin" approach is an improvement over the "safety factors" approach in that it provides an analytical method of evaluating the risk that an overstress or understrength condition will exist. Instead of a pyramid of safety factors imposed by each area providing the "worst case" value, the probability of failure is evaluated on the distribution of values. Figure 7-26 illustrates the comparison. The strength of material is quoted at the -3σ value, the computation of stresses is made at the mean value, the safety factor used is 5. By evaluation of the distributions the safety factor could very realistically have been set at 3.

The analysis attempts to evaluate the probability of finding a value of stress much larger than (or strength much less than) the nominal value. Where this probability is high, the safety margin must be great, where the probability is low, a small margin will suffice. Where this probability is not capable of estimation, approximations must be used and a contingency factor based on the objective knowledge obtained from testing or analysis applied.

The purposes of safety margin analysis is to improve the competitive position of the design; that is, to find the optimum comparison of stress and strength that will (a) have an acceptable probability of success and (b) compare favorably with other constraints such as weight, cost, availability of material. My favorite example is the assumption made years ago that brick and mortar could stand a tensile load. Tests confirmed this and using a tensile stress loading in the design of large furnace chimneys of one pound per square foot, the industry was revolutionized by the appearance of tall, skinny (to them) chimneys.

Recognizing that while in most shipbuilding material the standard deviations of strength, with the usual manufacturing control and

OVERDESIGN FROM SAFETY FACTORS



inspection, is negligible in comparison to the yield and ultimate strengths, the stresses imposed by dynamic loading may be highly probabilistic in nature. There were a number of Jeep aircraft carrier that suffered damage to their flight decks during the war due to heading into seas during hurricane force storms. Consideration was given to greatly strengthening the structural support. A decision was made (in the CNO as recommended by the Bureau) that the probability that the situation would need to occur, that carriers would need to recover aircraft in a hurricane, was small enough to make the (then) present design acceptable. Fleet and Task Group commanders were informed of the limitation on the ships capability and told to avoid the situation.

The selection of the appropriate working stress, for competitive design, should consider the nominal maximum loading anticipated but should also consider the distribution of loadings which may cause stresses in excess of this value (as probability that a ship must proceed on a particular course with relation to a hurricane). The strength computation should be based on an acceptable value of risk, as opposed to a nominal stress value hoping the safety factor is adequate to prevent failure when the extreme occurs.

Use of the stress-strength approach provides the engineer with one more analytical tool to assist in reaching decisions in the process of design and development of systems.

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Chapter 8

MAINTAINABILITY

Chapter 8

MAINTAINABILITY

Maintainability concepts are being emphasized in all services of the Department of Defense because of the high costs associated with maintaining equipment operational. Three closely associated problems have increased maintenance costs within the Navy. Following World War II came a tremendous increase in complexity of ships equipment. And ships became more specialized. This was accompanied by an increase in the turnover of personnel. As the equipment became more difficult to maintain, the capabilities of the maintenance personnel fell behind; they were less able to cope with the problems. The approach being taken by the services is to increase the maintainability of systems.

Maintainability is the speed or economy with which a system or component can be kept in, and/or restored to, full performance capability. A principally-used measure is the average number of failures restored per hour of Corrective Maintenance time, which is the reciprocal of MTTR. Another is the fraction of attempts wherein restoration is completed in a specified time, or the probability that it will be completed in that time. Another is the operational time per dollar cost of preventive and corrective maintenance.

The objectives of a maintainability program include the perfection of the design to assure that maintenance actions can be accomplished in minimum time, with minimum effort but with maximum safety.

By the above definition, we find ourselves concerned with four areas of enquiry:

(a) The capabilities and characteristics (both mental and physical) of the people who maintain and operate the system,

(b) The design of equipment suited to the characteristics of such people,

(c) The quantification of requirements, prediction, and verification to control the achievement of maintainability and assure ourselves that the system meets our needs, and

(d) The management control of maintenance resources.

Maintainability is often confused with maintenance. The achievement of maintainability is a design function, but maintenance is a consequence of design and use. There are two other similar terms that can be confusing; maintainability analysis and maintenance analysis. The design function that analyzes equipment and systems to determine what operation and maintenance actions are required to keep equipment or systems operating does maintainability analysis. Analysis of maintenance tasks to determine the resources required to do the work is maintenance analysis. Resources again mean men, money, material, facilities, time and morale.

One military specification (5) has the following requirements for maintainability analysis and maintenance analysis.

> "Maintainability Analysis. A maintainability engineering analysis of the system shall be accomplished concurrently with the design effort. This analysis shall provide a definition of maintainability design features to be incorporated in the hardware. This analysis shall be used to evaluate the degree of achievement of the maintainability design goals, including inherent mean and maximum down time, the logistic and personnel subsystems decisions related to support cost of the system versus design and support alternatives. The primary inputs into the maintainability analysis will be data obtained from design engineering reports, data and studies prepared by the contractor, and the requirements furnished by the procuring agency."

> "Maintenance Analysis. The contractor shall conduct a detailed determination of hardware maintenance tasks, tools and test equipment, and spares line item identification. This is a portion of the over-all system analysis and provides feedback to the maintainability analysis."

It is obvious that the two types of analysis cover the same ground. The designer must, in his design foresee the maintenance tasks that will be required to maintain and operate the equipment if he is to incorporate features into the design to improve the ease and economy of repair or maintenance. For optimization of the maintainability of the design includes design for minimum support requirements as well as access and simplicity of required operations. To achieve this will require a rather detailed task analysis which will be partially duplicated by the subsequent maintenance analysis. Reasonable efficiency requires that the two efforts be married from the concept of the design not only to reduce duplication of effort, but to prevent different maintenance concepts from being developed, as will usually occur unless the two are coordinated.

Accepting that the perfect machine - one designed to perform its function whenever called upon and never to have a failure - has yet to be designed, we realize we must accept something not quite perfect. But how much less than perfect? The answer must be based on the function the system is required to perform.

There are two primary roads we can follow. We can spend every dollar we can afford to make the system reliable - to reduce the the incidence of failures so that it almost never needs to be repaired. Or we can permit the system to fail, as often as it needs to, spending our money in the design to make it almost instantly restorable. This second approach is called maintainability. As might be expected, the best and most economical approach is usually somewhere between these extremes.

Lets take an example. The functional requirements in terms of consistency of performance are different for the refrigerators on a freighter than for the steering engines of the same ship. The consequences of failure in the steering engines are immediate - lack of control, usually with the rudder hard over. Collision or grounding are predictable consequences. The refrigerator, on the other hand, can maintain a low temperature for a considerable time. Ultimately spoilage and logistic problems may result if not repaired soon enough, but immediate consequences are not foreseen.

In the case of the steering engine, we demand high reliability, a very low failure rate. To achieve this we provide duplicate systems so that, should one fail, the other can be used. For the refrigerator, no such instantaneous replacement is required. We rather require that the equipment be operable a high percentage of the time, with no extemely long down times. This latter characteristic we define as maintainability.

1. AVAILABILITY

1.1 INHERENT AVAILABILITY

The point of comparison between reliability and maintainability as a design approach is called Availability. Availability is the fraction of the total desired operating time that the system or component is operable (chapter 27). For prediction purposes it is also the probability that a system or equipment is operating satisfactorily at any point in time when used under stated conditions (1). We might consider a system such as the evaporators on board ship. The requirement for operation depends on the storage capacity and usage of fresh water. At any point in time the evaporators may be operating. If they are not, several possible reasons may account for their shutdown:

(a) Water tanks are full;

(b) Inadequate auxiliary exhaust steam makes their use uneconomical;

(c) Polluted harbor water makes operation undesirable;

(d) Evaporators are down for maintenance;

(e) Evaporators are down for repair.

Considering only the last reason, Figure 8-6 provides a pictorial explanation of Inherent Availability, A_i.

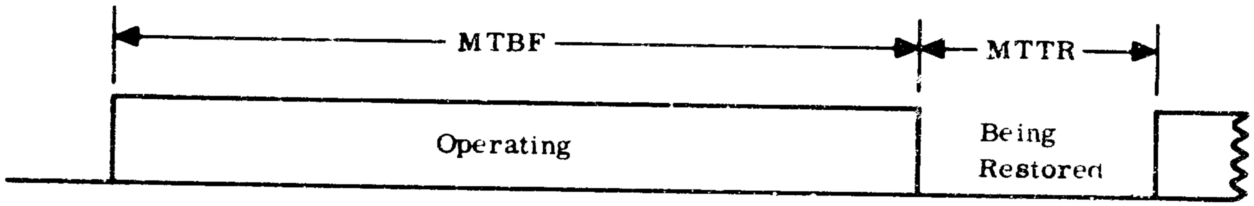
Inherent Availability (4) is the fraction of total time that a system or equipment, when used under stated conditions in an ideal supply environment, is capable of operation. Inherent Availability excludes time down except for the time necessary to diagnose the trouble, repair the fault, test out and restart the equipment.

The two components of Inherent Availability are Reliability and Maintainability. Reliability can be measured in terms of Mean Time Between Failures (MTBF). Maintainability is measured in terms of Mean Time to Restore (MTTR). Restoration is used in preference to repair since restoration is used in the sense of returning the system to operation by using replacements or possibly by switching on redundant elements, where repair may include welding a crack, or depot or factory repair of replaced modules subsequent to their removal. The measure, MTTR, is defined as the statistical mean of the distribution of times to restore. The summation of active restoration times during a given period of time divided by the total number of failures during the same time interval.

On the average, the equipment will operate a time equal to the MTBF before failure. On the average the equipment will be restored to operating condition in a time equal to the MTTR. The average time during which the equipment may be considered available is the fraction of the total time represented by the equation:

$$A_i = \frac{MTBF}{MTBF + MTTR}$$

INHERENT AVAILABILITY



Inherent Availability $A_i = \frac{MTBF}{MTBF + MTTR}$

1.2 OPERATIONAL AVAILABILITY

As pointed out earlier, it may not be possible to operate the equipment this fraction of the time. Most equipments require some down time for routine (scheduled) maintenance. Lack of spare parts or lack of manpower may delay the restoration action. Or administrative reasons may require the equipment to be shut down. The following terms are applied to non-operating time (4):

(a) Downtime: That portion of calendar time during which the item is not in condition to perform its intended function.

(b) Preventive Maintenance Time: The maintenance time to retain an item in satisfactory operational condition by providing systematic inspection, detection, and prevention of incipient failure. It is made up of performance measurement, care of mechanical wearout items, front panel adjustment, calibration and alignment, cleaning, etc.

(c) Corrective Maintenance Time: The time that begins with the observance of a malfunction of an item and ends when the item is restored to a satisfactory operating condition. It may be subdivided into Active Maintenance Time and Non-Active Maintenance Time.

(d) Active Restoration Time: The Corrective Maintenance Time during which work is actually being done. It includes detection, diagnosis, preparation, replacement or repair, adjustment, checkout, and reload time to the extent each is necessary.

(e) Active Maintenance Time: The time during which preventive and corrective maintenance work is actually being done on the item.

(f) Non-Active Maintenance Downtime: The time during which no maintenance is being accomplished on the item because of either supply or administrative reasons.

(g) Administrative Time: That portion of Non-active Maintenance Time that is not included in Supply Time.

(h) Supply Time: That portion of Non-Active Maintenance Time during which maintenance is delayed solely because a needed item is not immediately available.

(i) Inactive Time: The period of time when the item is available, but is neither needed nor operating for its intended use.

The term, Operational Availability (A_o), is used to describe that fraction of the total time that the system, when used under stated conditions in an actual supply environment, will operate satisfactorily when required. Supply time and Administrative time are included.

2. REQUIREMENTS

2.1 BASIC APPROACHES

OPNAVINST 3910.4A outlines how the Navy prepares Technical Development Plan Summaries. Enclosure 1 to the instruction defines the information to be included in sections of the summary. Sections 10 through 13 require information pertaining to maintainability. The four sections are titled:

Section 10	Dependability Plan
Section 11	Operability and Supportability Plan
Section 12	Test and Evaluation Plan
Section 13	Personnel and Training

The Dependability Plan of Section 10 sets up Availability and Operational Readiness Goals. Quantitative Reliability and Maintainability goals (MTBF and MTTR) can be set up from the availability and readiness goals. At the start of a project or in the project Definition Phase, only gross statements can be made for maintainability. Like system analysis, maintainability analysis is an iterative process which gets progressively refined as a project progresses.

At the end of a Project Definition Phase the following should be established for Maintainability Assurance:

(a) A maintenance philosophy is described for the system to provide essential data for the Supportability Plan and the Personnel Training Plan. The maintenance philosophy will develop:

(1) Echelons or levels of maintenance, including maintenance tasks and skills for each level.

(2) Planned use of built-in maintenance aids such as self-test features, malfunction indicators, specialized or standard test equipment, etc.

(3) Planned use of job aids such as troubleshooting logic charts, system technical manuals, audio-visual presentation of maintenance tasks, etc.

(4) Other design features which may affect spare parts and repairs such as use of standard circuits from specific handbooks, disposable modules, etc.

(5) Unique knowledge of skills required by the system.

(6) Equipment utilization or operational cycle.

(7) Maintenance environment.

(8) Maintenance facilities.

(b) Applicable MIL specifications are defined.

(c) Quantification of Maintainability, i.e., development and application of numerical measures of maintainability.

(1) Mean Time to Restore (MTTR)

(2) Maximum Time to Restore (MAXTR)

(3) Other

(d) Maintainability apportionment and prediction. This involves the allocation of over-all system measures of maintainability to all major lower-order elements of the system, with special regard for maintenance tasks, times and test equipment required at the various echelons involved. It also includes data concerning the extent, schedule, design, influence, etc. of prediction in the over-all plan for Maintainability assurance.

(e) Maintenance tasks and skill analysis.

(f) Maintainability design reviews.

(g) Test and demonstration.

(h) Maintenance data collection, feedback and analysis.

The maintainability assurance plan will vary in complexity with the size of the project and careful evaluation has to be made of the benefits to be received from the expenditures to be made.

A proposed DOD instruction titled "Development of the Weapon System or Equipment Integrated Support Package," defines the role of the material manager in and the minimum requirements for the systematic and orderly development of the weapon system or equipment integrated support package."

The elements of an Integrated Support Package are:

1. Planned Maintenance
2. Logistics Personnel Subsystem
3. Logistics Data
4. Support Equipment
5. Spares and Repair Parts
6. Facilities
7. Contractor Support

It can be seen that the elements of an Integrated Support Package are closely aligned to the Maintainability Assurance portion of the Dependability Plan outlined in OPNAVINST 3910.4A.

2.2 SPECIFICATIONS

All of the services are implementing the DOD directive and instructions with specifications and handbooks on maintainability. MIL M 23313 (SHIPS)(2) outlines a comprehensive program for maintainability of electronic equipment. For maintainability design guides, it refers to Navy Publication NAVSHIPS 94324. The specification covers maintainability during design and production. It covers maintainability prediction during the preliminary design stage. Maintainability requirements are noted for the final design stage, preproduction stage and during production. Equipment Repair Time (ERT) is used as the measure of maintainability.

The Appendix to specification MIL M 23313(SHIPS) covers "Maintainability Design Evaluation Procedures" in detail. It is specifically slanted at electronic equipment and excludes mechanical hardware from the evaluation procedures. Although the title of the Appendix does not indicate it, maintainability prediction techniques are given for the early and late development stages of design.

3. QUANTIFICATION OF MAINTAINABILITY

3.1 RELIABILITY-MAINTAINABILITY TRADE-OFFS

The selection of the design approach, whether to use reliability or maintainability approaches to achieve the required availability, is based on the functional requirements for the system. Reference (6) provides useful techniques in the development of reliability-maintainability trade-offs. In making the choice, the following factors should be kept in mind.

(a) Even highly reliable systems will have some failures. When high reliability during short time intervals in required, as in the steering engines, high availability achieved through reducing the MTTR may not be pertinent, unless the restoration is practically instantaneous.

(b) An improvement in reliability by quality improvement (simpler design, parts and manufacturing process control, etc.) will reduce the costs attributable to repairs. An improvement in reliability through use of duplicate equipments, each of lower reliability will <u>increase</u> the costs of maintenance and repair.

(c) Equipments with low MTTR achieved by modular design, have a tendency to increase the cost of repair. When the low MTTR is achieved by planning for maintenance and repair in the design phase, costs of repair tend to go down.

Reliability and Maintainability in design must be traded-off to achieve a system or equipment design which will:

(a) Satisfy a specified availability goal.

(b) Satisfy design and mission constraints.

(c) Result in design optimization with respect to cost, performance and schedule.

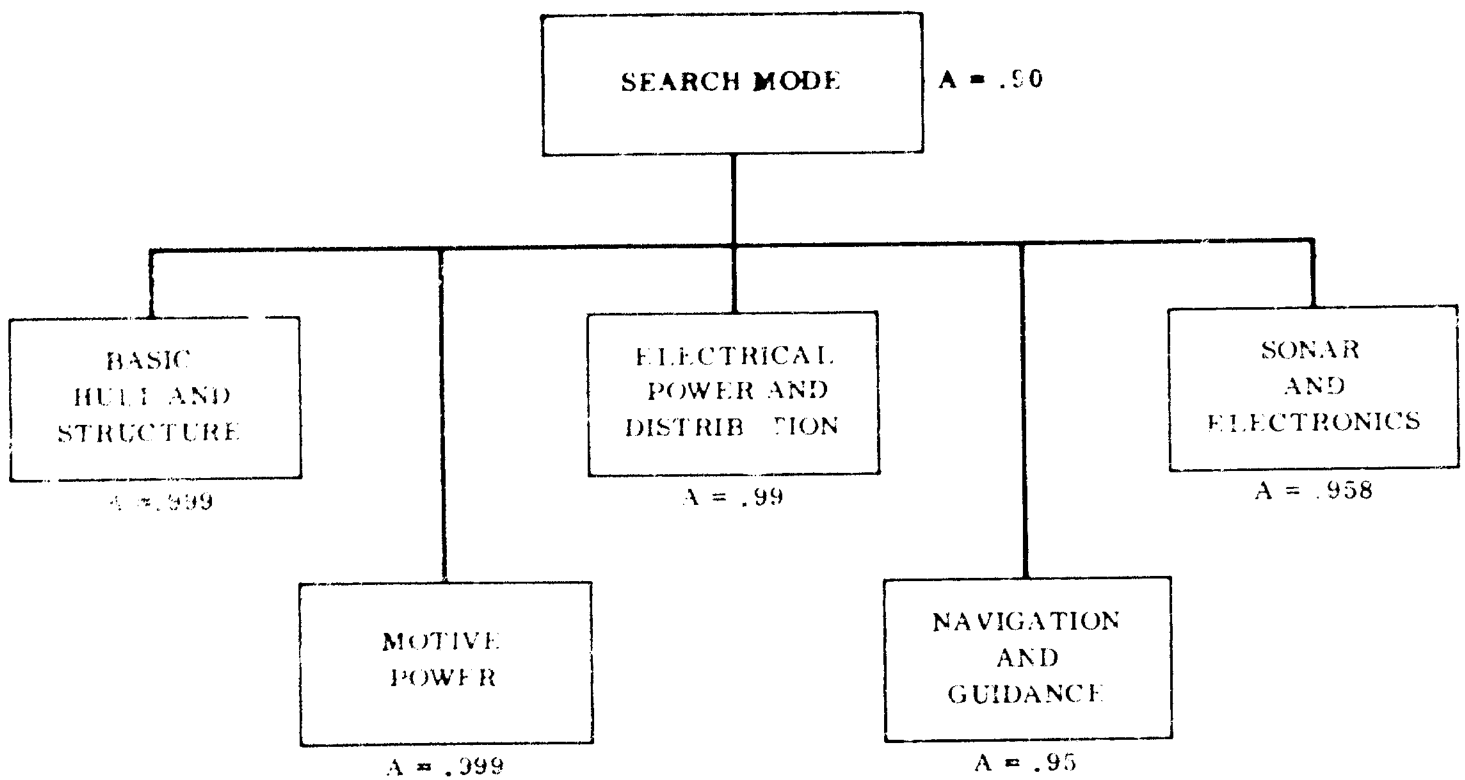
Satisfaction of the mission goal -- achievement of a given level of availability -- is determined by the system/equipment MTTR and MTBF. MTTR is generally determined to a large degree by (a) the prime equipment and associated test equipment designs as they relate to the "on-line test approach", and (b) the packaging design as it relates to the time required to find, remove and replace a failed element -- principally correlated with the "Functional level" of the replaceable element and thus with the extent of the troubleshooting task leading to correction. MTBF is primarily determined by the approach taken toward improving the reliability of the total population of parts in satisfying the mission performance requirement.

In order to proceed deeper into these trade-offs it is necessary to define the various levels of performance or operational modes for the system. For a surface ship, one of those might be the "search" mode for which we have a specified operational availability of 0.90. Next, we must describe all the equipment, personnel, and facilities required to support the search mode. Essentially it means going through the system logic for each concept under study and using the system model (discussed in Chapter 3) to develop a failure effects analysis at the functional level. Since functions relate to hardware, the following maintainability characteristics can be determined: a) feasibility of performing maintenance, b) necessity for "designing in" ease of maintenance, c) supporting hardware such as tools, test equipment, checkout gear required, and d) personnel required for maintenance and their skill levels. The above analysis must be performed in parallel with reliability analysis in order to allocate availability to the end item. Even highly reliable systems may have an unacceptable level of Availability if a failure requires an excessive amount of time to return to satisfactory operation.

The top level availability requirement can be apportioned among the end items required for the search mode using standard reliability apportionment techniques discussed in Chapter 6. The Failure Effects Analysis is an aid in performing this. A hypothetical apportionment is shown in Figure 8-13. Further discussion of the example will concentrate on the SONAR and ELECTRONICS end item for which the assessed Availability goal is .958. We are now faced with the task of optimizing the balance between the Reliability parameter (MTBF) and the Maintainability parameter (MTTR). Obviously there are a number of trade-offs as shown in Figure 8-14, which can achieve the Availability requirement with an MTTR constraint of .12 days downtime failure (2.88 hrs.).

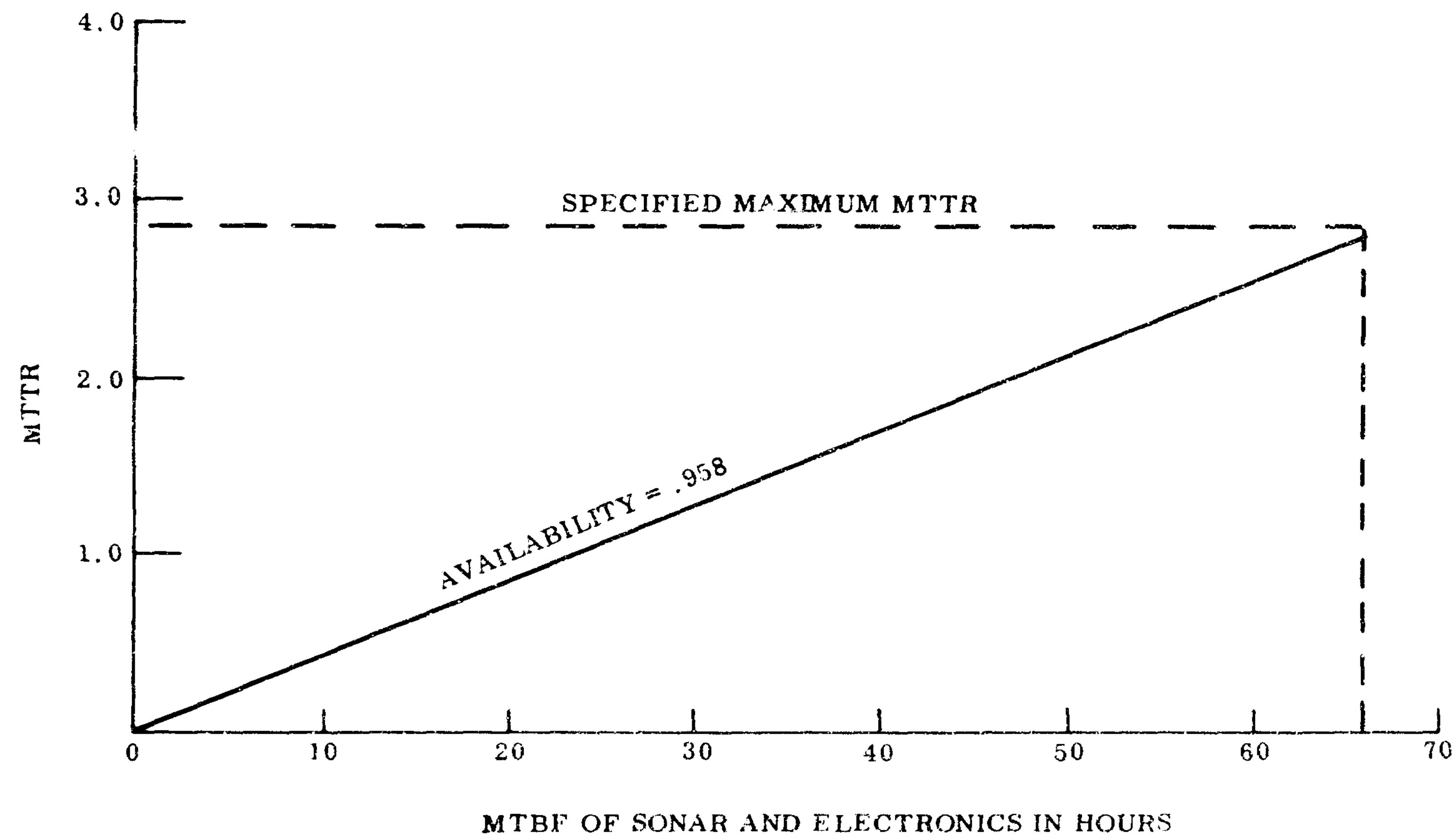
Now that certain constraints have been placed on the hypothetical

SEARCH MODE APPORTIONED AVAILABILITY



RELATION OF MTTR TO MTBF

For Availability = .958



subsystem, a Maintenance Policy Study is conducted in order to determine what values of MTBF and MTTR seem to be reasonable. Concurrently, reliability analysis determines what particular values of MTBF seem reasonable in light of projected state-of-the-art, development test requirements, costs, etc.

Items which are included in the maintenance policy study are:

(a) Maintenance Policy Study

1. Appropriate echelon for repair
2. Module size determination
3. Repair versus discard decisions
4. Test and checkout philosophy
   - Degree of automation
   - Inspection interval
   - Special test equipment
5. Preventive maintenance schedule
6. Role of man in system
   - Classification/functions
   - Task definitions
7. Safety Requirements
8. Appropriate Provisioning Policy

(b) Technician Requirements

1. Selection
   - Education
   - Experience
   - Aptitudes
   - Motivation
2. Training
   - Task analysis
   - Procedures
   - Equipment
   - Programmed learning
3. Validation of Proficiency
   - Experimentation
   - Man/system compatibility
   - Capabilities analysis

(c) Time Requirements for Corrective Maintenance

1. Localization time
2. Isolation time
3. Disassembly time
4. Interchange time

5. Reassembly time
6. Alignment time
7. Checkout time
8. Degradation factors for operational use.

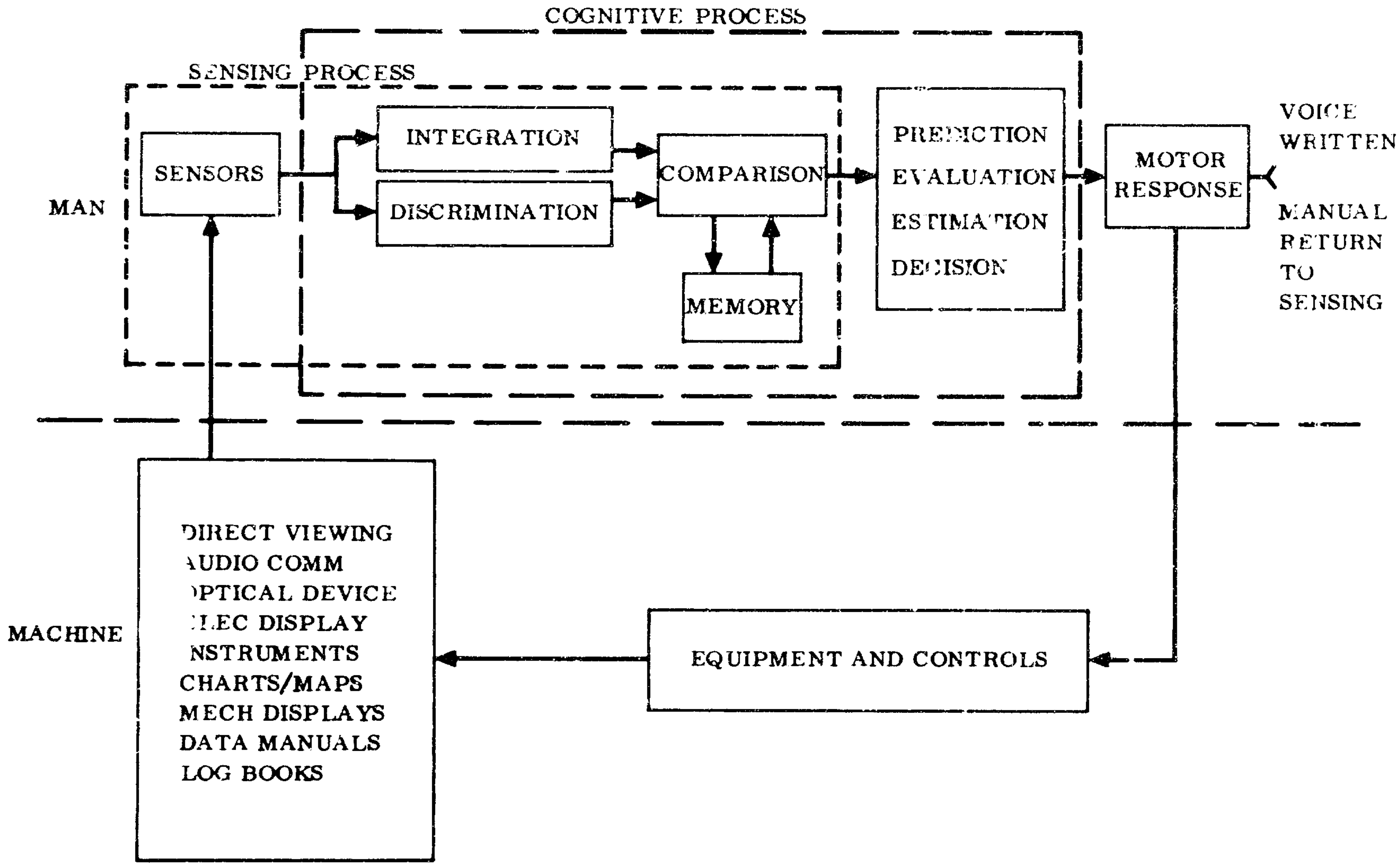
The interrelationship of these items for Maintainability is such that a change in one will affect another in terms of: a) the duration of system failure, b) the duration of component failure, and c) the system cost initially and over its lifetime of use. The elements are compared in a systems evaluation model to determine the effect of the downtime of a system on availability relative to costs. Costs can be taken into account by determining manhours required, additional facilities and trade-offs between costs of items in the supply pipeline versus item downtime.

With the establishment of the Maintenance policy, large scale decision-making and trade-offs are essentially complete. Availability, maximum and mean allowable downtime, and minimum acceptable reliability have been assessed to the end item level and quantified for insertion into the system specifications. Should a decision be made to proceed with pure hardware development, these will become design requirements. Note that there is still some latitutde remaining for design in that increased reliability can be substituted for decreased maintainability at the black box level.

In dealing with the derivation of Maintainability requirements the man/machine interface must continually be evaluated. In shipboard practice, the operator is seldom the maintenance technician and in this section the difference should be distinguished. First, we are concerned with the operator and his role in system availability. His role, that of failure detection and partial diagnosis, is like that of a computer with many feedback loops. His motor response (see Figure 8-17) is a result of how well the machine can tell him its status during normal operation and its troubles when failure occurs.

Figure 8-17 also applies to the maintenance technician. That is, there are many alternate modes in which he receives information during the process of system restoration (i.e., correction and verification). However, no matter how well a design is optimized for man's sensing and cognitive process, the total job of maintenance cannot be performed until the physical constraints such as space, and weight have been overcome for him to produce this "motor response."

MAN-MACHINE INTERFACE



3.2 ACHIEVEMENT OF MAINTAINABILITY

All we have done so far is to define the system, its operation and its design requirements. The process of detail design now gets underway and it becomes Management's job to assure that specific maintainability requirements are being met. The road-block to maintainability assurance lies in getting the designer to work with the tools of Maintainability. He must be informed as to what items he must consider when designing equipment. It is at this point that manuals (7 and 8) become a great help.

Achievement of maintainability requires an integration of the maintainability tasks into the design cycle. In each step, the maintainability engineer is supporting the designer in his effort. The phasing of this support and its integration into the program are indicated in Figure 8-19. Design toward required maintain-ability requires most of the program aspects already discussed for reliability. Certainly training and indoctrination of those who will ultimately influence the final product (designers, pro-duction, etc.) is as important here as in reliability achievement. Day to day liaison with the designer will provide the same rewards, understanding and acceptance of the discipline. Participation in Design reviews from concept to final drawing release provides a medium for training and development of understanding in the design areas. As with reliability, unless the designer has a comprehen-sible (to him) goal and understands (or can be taught) the prin-ciples that will enable him to achieve it, the effort of trying to make the equipment meet a maintainability requirement is fruitless. A maintainability program commences during the pro-posal/precontract study phase and continues through design, de-velopment, fabrication, testing, and delivery of equipment to the customer. Major program tasks include the accomplishment of:

Design Analysis (Liaison) -- the systematic approach whereby maintainability requirements are achieved effectively and economically in the initial equipment design.

Maintainability Analysis -- a continuing review of the de-sign to determine the degree of maintainability requirements incorporated in equipment design.

Maintainability Demonstration -- a final hardware verification of the actual degree of maintainability requirements incor-porated in equipment design.

One facet of achievement of maintainability is the establishments of these requirements and their use as a design control tool as

MAINTAINABILITY PROGRAM

(Typical Program Phases)

Proposal and Precontract Study	Initial Design	Advanced Design and Fabrication	Integrated Test and Demonstration
1. Review Program Requirements	1. Generate Policies & Procedures	1. Update M Critieria as required	1. Continue M Analysis
2. Define Program Objectives.	2. Establish M Criteria.	2. Monitor Supplier Effort.	2. Conduct Phase II M Demonstrations
3. Define Program Management & Organizational Approaches	3. Initiate Supplier Work Statements Monitor Supplier Effort.	3. Continue training & Indoctrination	3. Collect M Data
4. Review System Technical Requirements	4. Update Maintenance Concept.	4. Continue Design Liaison Activities	4. Initiate Design Changes as Required to meet M Requirements
5. Define Preliminary Maintenance Concept.	5. Start Training & Indoctrination.	5. Continue M Analysis	
6. Conduct Preliminary Trade-off Studies.	6. Implement Design Liaison Activities.	6. Accomplish Phase I M Demonstrations	
	7. Initiate M Analysis	7. Collect and Evaluate M Data.	
		8. Monitor Design Changes	

presently specified in MIL M 23313(2).

In the design to achieve a specified maintainability requirement, Appendix to reference (2) describes maintainability prediction by the task analysis approach specified for electronic systems. The requirement is specified as an equipment repair time (ERT). The specification requirement is derived from the equation:

$$\text{ERT (specified)} = 0.37\ \text{ERT}_{max}$$

ERT_{max} is the maximum value of ERT that should be accepted no more than 10% of the time. The factor 0.37 results from the distribution assumed and assures a consumers risk of 10% when applied as specified.

Maintainability prediction can be initiated in the early development stage, when at least the following have been established:

(a) The planned packaging arrangement to the extent that a functional level breakdown into the various equipments, groups, assemblies, and subassemblies can be determined.

(b) The planned diagnostic procedure to the extent that the general levels of localization and isolation can be determined.

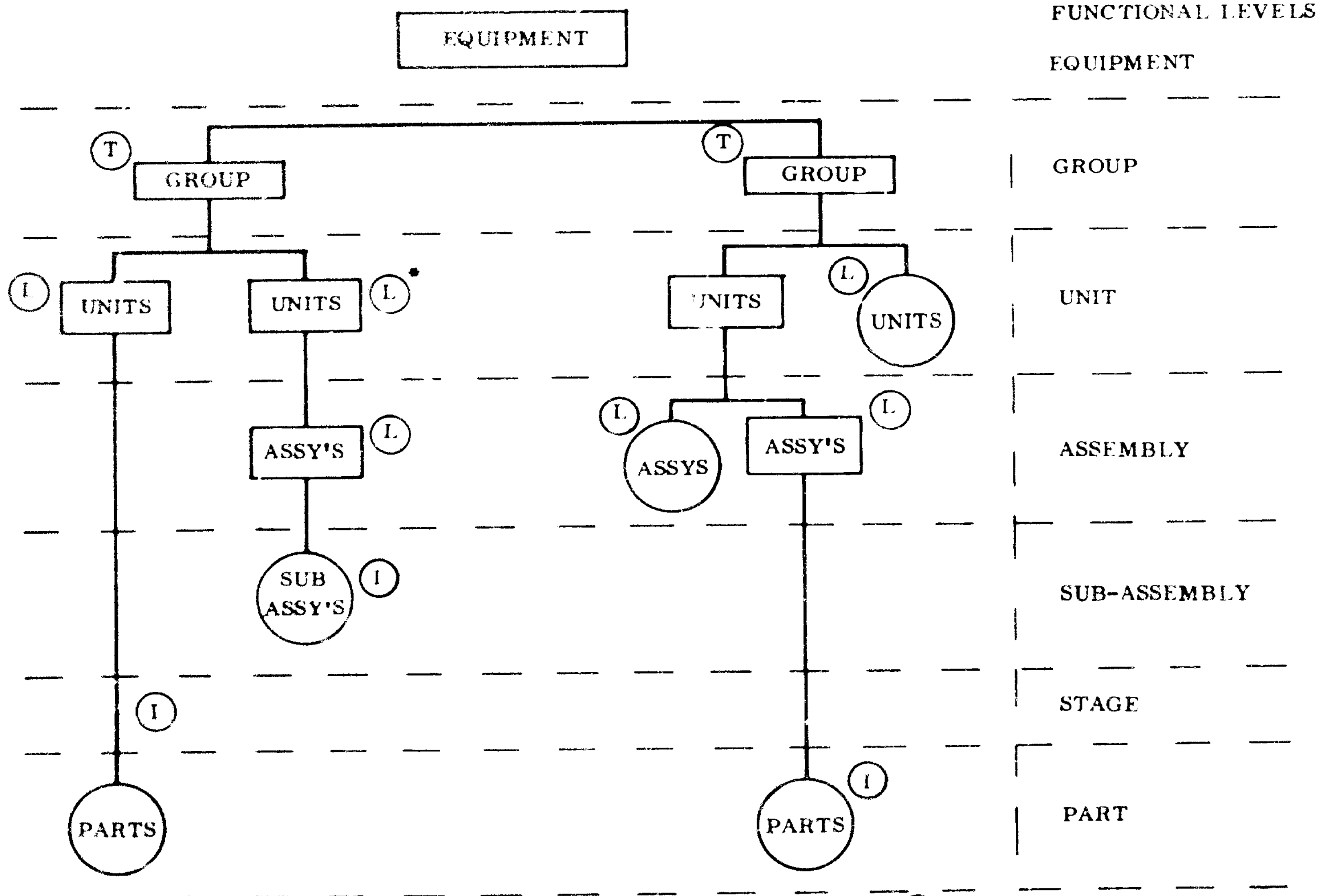
(c) The planned replacement method to the extent that the general method of failure correction can be determined; that is, whether individual parts, subassemblies, assemblies, or units will be replaced in making repairs.

(d) The approximate quantity of various categories of high failure parts such as tubes and relays to be included at each equipment subdivision.

(e) The level at which normal equipment operation will be confirmed following a repair.

The first step in the procedure is to determine the functional level breakdown of the equipment or system. This is done by dividing the equipment or system into its various physical subdivisions beginning with the highest subdivision and continuing down to the items such as parts, subassemblies, assemblies or units that will be replaced in corrective maintenance. The functional level breakdown is most easily established and certain determinations required during the prediction are more easily made if a functional level diagram similar to that shwon in Figure 8-21 is prepared. Here, a hypothetical electronic equipment is subdivided

EQUIPMENT FUNCTIONAL LEVEL DIAGRAM



LEGEND: (L) LOCALIZATION POINTS (I) ISOLATION POINTS (T) TEST (CHECKOUT) POINTS

* FOR PARTS MOUNTED IN UNIT

into its various groups units, assemblies, etc., down to the item that will be replaced during corrective maintenance. Each block within the diagram indicates all items having the same main-maintainability features. For example units repaired by replacing individual parts with localization to the unit level, isolation to the stage level, and test at the group level have been combined and represented by the "Units" block labeled (a) in the left hand branch of Figure 8-21. Each branch of the diagram is terminated with a circle which indicates the type of item that will be replaced to correct malfunctions existing in that branch. The connecting lines indicate maintainability relations and not electrical or operational connections. In preparing such a diagram care must be exercised in establishing the appropriate functional levels for the various subdivisions, especially where an item may have a nomenclature that includes the name of one of the functional levels (for example, "Power Amplifier Assembly"). In some instances, the functional level location of an item may not be the same as its nomenclature indicates.

After the functional level breakdown has been established and the functional level diagram prepared, the functional levels at which localization, isolation, access, and test features are applicable should be determined based on the overall characteristics of the design. The functional levels at which features for localization, isolation, and test are effective for each replaceable item can be indicated on the functional level diagram as shown by the symbols. The access functional level can be determined directly from the functional level diagram as indicated in (c) below, therefore, a symbol identifying it is not required. The functional level at which each of these features is effective is determined and shown in the functional level diagram as follows:

(a) Localization. - The functional level to which a failure can be located without using accessory test equipment is indicated by L.

(b) Isolation. - The functional level to which a failure can be located using accessory test equipment at designed test points is indicated by I.

(c) Access. - The access functional level for a replaceable item is that level to which disassembly must be accomplished in order to gain access to the item that is to be replaced, and from which reassembly must be accomplished after replacement of the item. This can be determined directly from the functional level diagram as the functional level of the first rectangular block above the replaceable item. For example, to replace a part in the left hand "Units" block, access must be gained to the unit level, and to replace a subassembly, access must be gained to the assembly level.

(d) Test. - The highest functional level at which restoration to normal service can be verified using self-test features or other testing facilities is indicated by T.

The actual prediction is performed in accordance with the following instructions.

(a) Calculating Repair Times (R_p). - The repair time (R_p) is calculated for each category of replaceable item indicated by a circle in the functional level diagram. It is the sum of the maintenance task time intervals determined from Figure 8-24 in the following manner.

1. Localization. - The localization time interval is determined by entering the chart using the column headed by the type of item that will be replaced (indicated by a circle in the functional level diagram) and continuing down this column to the row with the "Localization" column is the value to be used. If the replacement items under consideration are individually replaced parts use the value under "W" since wired in parts normally out number plug-in subassemblies, assemblies or units, use the value under "P".

2. Isolation. - The isolation time interval is determined in the same manner as the localization time interval except that the row for entering the "isolation" column is determined by the functional level to which isolation features are effective. This would be the level marked with I in the appropriate branch of the functional level diagram. The value indicated at the intersection of this row with the "isolation" column is the value to be used.

3. Access. - The access time interval is determined by entering the chart using column 1 (headed "Part") and continuing down to the row designated by the functional level to which access must be gained in order to perform the replacement tasks. The access functional level for a given replaceable item can be determined from the functional level diagram as the functional level of the first rectangular block above

CORRECTIVE MAINTENANCE TASK TIMES

FUNCTIONAL LEVELS				AVERAGE TIME IN HOURS TO PERFORM TASKS							
4	3	2	1	Locali-zation W	Locali-zation P	Isola-tion W	Isola-tion P	Access W	Access P	Test	Interchange
Unit	Assembly	Sub-assembly	Part	0.0	0.0	0.8	0.3	2.6	0.8	0.2	Parts 0.2
Group	Unit	Assembly	Stage	.0	.0	1.2	.3	.9	.6	.2	
Equipment	Group	Unit	Sub-Assembly	[illegible]	.1	1.4	.4	.4		.2	
Subsystem	Equipment	Group	Assembly	1	.1	1.6	.5	.3		.2	
System	Subsystem	Equipment	Unit	.1	1	1.7	.6	.2		.1	Subassemblies, Assemblies, and Units 0.1
None	System	Subsystem	Group	.1	.1	1.8	.8	.2		.1	
	None	System	Equipment	.1	.1	1.9	.9	1		1	
		None	Subsystem	.1	.1	2.0	1.1	1		.1	
			System	.2	1	2.1	1.3	0		.1	
			None	.2	.1	2.2	1.6	0		.0	

W – For individually Replaceable Parts

P – For replaceable subassemblies, assemblies and units the replaceable item. The value indicated in Figure 8-24 at the intersection of this row with the "access" column is the value to be used.

4. Test. - The test time interval is determined by entering the chart using column 1 and continuing down to the row designated by the functional level at which restoration to normal service is verified. This would be the functional level indicated by T on the functional level diagram. The value indicated at the intersection of this row with the "Test" column is the value to be used.

5. Interchange. - The interchange time interval is either 0.1 or 0.2 hours as shown in the right hand column of Figure 8-24. The time indicated for sub-assemblies, assemblies, and units (0.1 hours) apply to these items only. The time indicated for parts (0.2 hours) is applicable to all individually replaced parts. The values given for interchange times are average times for these classes of items, and include handling an average amount of hardware such as nuts, bolts, and other retaining devices. The repair time (R_p) is the sum of the time intervals for each task.

(b) Calculating MTTR. - After an R_p for each circle of the functional level diagram has been calculated, the MTTR should be claculated using the following expression:

$$MTTR = \frac{K_1 R_{p1} + K_2 R_{p2} + \ldots K_n R_{pn}}{K_1 + K_2 + \ldots K_n}$$

where:

R_{p1}, R_{p2}, ...R_{pn} are the repair times for replaceable items having the same maintainability features (items within each circle on the functional level diagram).

K_1, K_2, ...K_n, are numbers which are approximately proportional to the quantities and relative failure rate of selected high-failure parts grouped within a circle containing replaceable items having the same maintainability features. The high-failure parts considered are those that will contribute the majority of the equipment failure.

The weighting factors (K) are determined from the expression:

$$K = NRT + \frac{1}{3}(ND) + \frac{1}{9}(NTr) + \frac{1}{3}(NRel) + 3(NRes) + 60(NMag) + 3(NCRT) + 5(NTT) \qquad (8.1)$$

where:

NRT is the number of receiving tubes in the group of items within a circle containing replaceable items having the same maintainability features.

ND is the number of semiconductor diodes in the group.

NTr is the number of transistors in the group.

NRel is the number of relays in the group.

NRes is the number of resolvers in the group.

NMag is the number of magnetrons in the group.

NCRT is the number of cathode ray tubes in the group.

NTT is the number of transmitting and special purpose tubes in the group.

The proportionality constants in expression (8.1), such as $\frac{1}{3}$ and $\frac{1}{9}$ are approximately equal to the average part category failure rates normalized relative to the average failure rate for receiving tubes.

In the later stages of design, the prediction of maintainability follows the same approach with the exceptions:

(a) The functional levels are defined in paragraph 4, Section 3 of Reference (8).

(b) Average part failure rates are selected from Reference (7).

(c) Using a form similar to Figure 8-27, record number, failure rates and maintenance task times for individually replaced parts, replaceable modular assemblies or units as applicable.

MAINTAINABILITY PREDICTION WORKSHEET

1. ITEM ______________________________

2. METHOD OF REPAIR: Replace - Parts Subassembly Assembly Unit SHEET ____ OF ____

3. PART CATEGORY	4 N	5 λ	6 $N\lambda$	MAINTENANCE TASK TIMES 8 LOC	9 ISO	10 ACC	11 ALIN	12 CHEC	13 INT	14 R_p	15 $N\lambda R_p$
		7. SUM								16. SUM	

The product $N\lambda$ is the total number of failures per million hours expected to be attributable to all parts in the respective category. The sum of all the "$N\lambda$" values represents the total number of failures per million hours attributable to the item covered by the worksheet.

Estimated times for the maintenance task are taken from the tables in Reference (2). The calculated repair time (R_p) is the sum of times for individual tasks. The product ($N\lambda R_p$) is the total repair time per million hours for the category. The sum of the $N\lambda R_p$ column represents the total repair time per million hours expected to be required by the item identified at the top of the worksheet.

After all worksheets are completed, the data should be consolidated on a summary sheet such as that shown in Figure 8-29. Entry of data on the summary sheet and calculation of MTTR is as follows:

(a) List the designation of the item covered by each worksheet in the "Item Designation" column of the summary sheet.

(b) List the sum of the $N\lambda$'s from each worksheet in the "$N\lambda$ Sums" column of the summary sheet opposite the respective item designation.

(c) List the sum of the $N\lambda R$'s from each worksheet in the "$N\lambda R_p$ Sums" column of the summary sheet opposite the respective item designation.

(d) Record the totals for the "$N\lambda$ Sums" column and the "$N\lambda R_p$ Sums" column at the bottom of the respective columns.

Calculate the predicted MTTR as indicated at the bottom of the summary sheet.

3.3 PREDICTION FOR MECHANICAL SYSTEMS

The approach to prediction of mechanical systems is essentially identical. Prediction of repair times can be initiated when:

(a) The design has progressed to the point that the major parts are determined.

(b) The planned replacement method can be determined; that is, whether parts, components, assemblies or units will be replaced in making repairs.

MAINTAINABILITY PREDICTION SUMMARY

EQUIPMENT OR SYSTEM ____________ SHEET ________ OF ________

ITEM DESIGNATION (1)	Nλ SUMS (7)	NλR SUMS $P_{(16)}$
TOTALS	A	B

$$\text{MTTR} = \frac{B}{A} = \underline{\hspace{3cm}} = \text{Hours}$$

(c) The maintenance schedule is established.

The prediction begins with the determination of the functional level breakdown of the system. A functional level diagram should be used for completeness. Parts that would be replaced simultaneously should be treated as a single assembly. Where different modes of failure (see Chapter 12) will cause a difference in the repair or restoration task, they should be treated as separate parts.

Using a worksheet similar to Figure 8-29, record the replaceable units (part, assembly or component level). Determine the expected failure rate of the part (by failure modes if applicable), assuming replacement of parts as prescribed in the maintenance schedule.

Compute the products $N\lambda$ as before, add and record in the space provided.

For each listed unit, estimate (as if you were planning the repair job) the length of time necessary to perform each step of the task. The normal steps in many mechanical repairs follow a pattern, such as:

(a) Diagnosis of trouble (localization)

(b) Isolation and cool down (isolation)

(c) Removal of obstructions (access)

(d) Disassembly (access)

(e) Repair or replace parts, including fitting, alignment, balance, etc. (replace)

(f) Reassembly (access)

(g) Replacement of obstructions (access)

(h) Restore normal conditions (purify, flush, etc.) (align)

(i) Test (test.

Compute the repair time R_p by summing the time for the individual steps. Where steps would normally be performed concurrently, the time for the combined operation should be estimated and recorded.

Compute and sum the $N\lambda R_p$ terms. The MTTR (inherent) is determined as before from the equation:

$$MTTR = \frac{\sum N\lambda R_p}{\sum N\lambda}$$

3.4 APPLICATION OF PREDICTION

The prediction of maintainability is used as a diagnostic tool. The MTTR just computed provides only part of the answer, the average restoration time. Where this time is excessive, the design, planned replaceable unit level, access or other factors must be improved. When an ERT_{max} has been required, an estimate of compliance can be obtained by summing all of the part entries for $N\lambda R_p$ that exceed the prescribed value, dividing this sum by the total sum of $N\lambda R_p$'s if the fraction exceeds 0.10, the equipment fails to comply.

The prediction is a useful tool in determining where best to apply the techniques for improving maintainability. Like reliability, maintainability can only be derived through sound, inherent design. The designer can only do this by an awareness of what the problems are and what tools exist to solve the problems. True, he should be aware of the quantitative downtime requirements which his system or equipment must meet, but he also needs the knowledge of 1) experienced specialists in maintenance analysis, and 2) human factors types and those who deal with the life sciences. In addition, handbooks such as NAVSHIPS 94324 should be made available to each design group. Much of the knowledge in these areas eliminates guesswork and gives the designer a firm basis for which to package the subsystem (end item) within the ship, the components within the subsystem and the parts within the components.

One of the more widely used techniques in industry is the Design Checklist, in conjunction with design reviews. Design checklists can be used to convert quantitative human engineering requirements into a qualitatively good design.

During the design, the designer should have before him continuously, the objective of making the equipment easy to maintain. Reference (8, 9 and 10) give comprehensive coverage of the design for maintainability of electronic equipment. Far less exhaustive are the details provided for designers of mechanical systems. Since mechanics are about the same size, build and strength as electronics technicians, many of the same rules, given in reference (8), apply. Reference (11) provides additional descriptions of the capability of operating and maintenance personnel.

Decisions as to the division of requirements among the seven major elements of downtime requires detailed cost studies. If we assume that meeting system downtime requirements means that we in fact do meet specified mission requirements, then the allocation problem becomes strictly an economic one -- i.e., attaining the specified downtime capability at minimum cost.

As an example, one of the primary means for reducing system downtime is to substitute automatic checkout and diagnostic equipment for the slower human operator and to use modularized, plug in components. Decisions to automate are generally made on a systems basis; the level to which automation would be carried (e.g., automatic fault isolation to a replaceable module level) would be determined by cost tradeoff studies. Results would establish consistent guide lines for allocating downtime requirements below system level to the subsystem and the component level.

The most time-consuming element of downtime is generally diagnosis. However, substitution of automatic diagnostic equipment and proper selection of the module size to which the failure will be isolated can reduce this time almost to zero. The same holds true for detection and verification, depending on the extent of automation desired. This leaves the "correction" element as the one which ultimately becomes the most limiting factor in this example.

Cost tradeoffs might indicate that it would be cheaper to go to redundant switch-in spares, thus reducing corrective time and eliminating some of the automatic checkout features. This is but one example of the many tradeoffs necessary to determine the least cost configuration and to define support items necessary.

The following characteristics (among others) affect the ease and rapidity of repair:

- (a) Accessibility, including room to operate tools required.
- (b) Clarity of instructions and diagrams.
- (c) Marking and identification
- (d) Displays, gauges, and controls.
- (e) Weight, including provision of handling gear & lifting pads.
- (f) Interchangeability.
- (g) Proper tools.
- (h) Visibility.

The cost studies involved in tradeoffs should include, but not be limited to:

(a) Cost of parts or modules.
(b) Cost or value of salaries of repair personnel.
(c) Cost of training or repair personnel.
(d) Cost of rework of modules at the factory, or repair activity (tender or shipyard).
(e) Administrative costs of procurement, storage and shipping.
(f) Costs of diagnostic, test and repair tooling.

3.5 MAINTAINABILITY PROGRAM CONSIDERATIONS

But prediction of maintainability is only one of the phases of the total program. Maintainability achievement requires the same comprehensive, across the board consideration as reliability. Figure 8-34 indicates the areas of program application, showing the interplay with design, reliability, logistic planning, training, software and support requirements.

4. MAINTENANCE ANALYSIS

Like system analysis, maintenance analysis is an iterative process that appears to be gigantic. It is a tedious process but it is controllable. In the Conceptual Phase of a project, gross statements based on experience have to be made for performance, maintainability, availability, etc. This is so because the conceptual phase of a project is a wish to develop something novel based on past experience. The past experience is the life saver that makes it possible to make gross statements with a fair degree of accuracy. Past experience also gives industry the incentive to propose novel projects or bid on them. Through continuous iterative analysis, the original gross statements evolve into workable hardware systems that meet performance requirements.

4.1 INTEGRATED MAINTENANCE MANAGEMENT

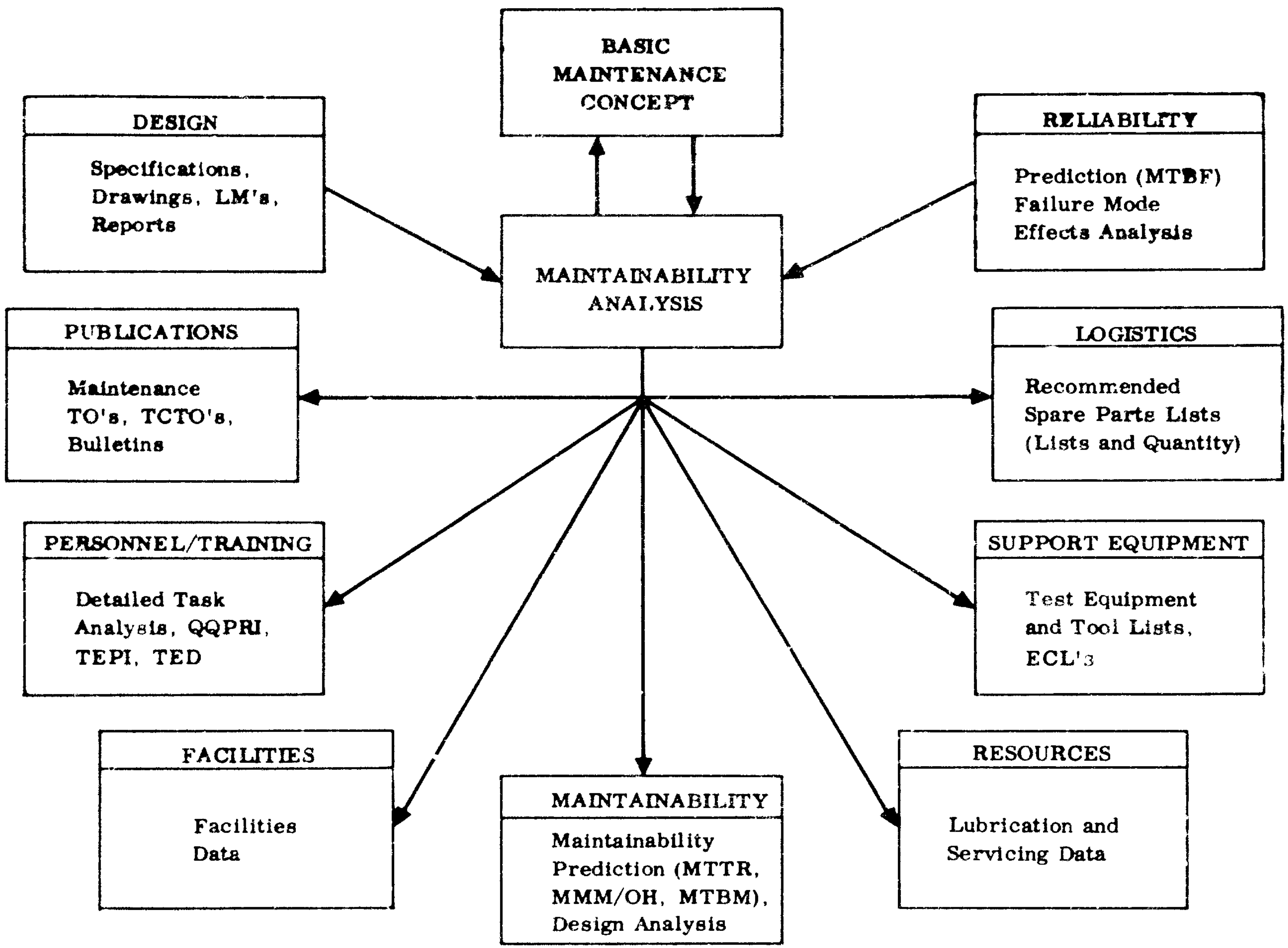
The integrated maintenance management concept (3) includes documentation in the form of Maintenance Engineering Analysis Records (MEARS) to control the data needed for maintenance analysis. See chapter 17.

The maintainability of the design is documented as follows:

1. The maintenance concept has been reviewed and confirmed.

2. The contractor's qualitative maintainability design features of the product have been verified.

MAINTAINABILITY PROGRAM



3. The maintenance requirements and tasks established for the article have been demonstrated.

4.2. MAINTENANCE CONCEPT

Analysis of a Shipboard Diesel Generator is used to show how a maintenance analysis is done. We have picked a 3000 brake horsepower diesel which has a fuel consumption of 0.42 pounds per brake horsepower hour. Two power plants are used to assure a continuous supply of power. If we assume the ship will have a three-month mission, then approximately 419,000 gallons of diesel fuel will be consumed on the mission. It is not practical to carry such a quantity of fuel on board ship so arrangements have to be made for resupply from tenders. This means piping has to be installed for taking the fuel from the tender to the diesel fuel tanks in the ship.

Various kinds of maintenance and operations will be required to keep at least one diesel generator operating at all times. A 90-day mission amounts to 2160 hours of running time which can be evenly distributed to each diesel for 1080 hours each. If the diesel generators are good for 3000 hours of operation between overhaul, the overhaul plans have to be made to do this after every third mission.

Instructions have to be provided to tell the technicians how to switch over from one generator to the other periodically. There will be light maintenance work required to keep the diesels running efficiently. Air and fuel filters will have to be cleaned periodically to remove accumulated carbon deposits. The crankcase oil has to be checked and replenished.

The operating generator has to be monitored to assure that the electrical output is consistent with requirements of the shipboard equipment. This information has to be provided as instructions for the technicians that do the work. Brushes on the generators have to be inspected periodically to assure they are not worn out. Since the brushes can wear out, provisions have to be made to stock spare brushes on the ship.

A detail analysis has to be made of the diesel and generator to determine which parts will have to be replaced at the 3000-hour overhaul period. This analysis will be based on experience with existing diesel generators or if it is a new design, experience with similar designs will be used. The detail analysis will develop data for use in overhaul manuals, provide a list of repair parts for an overhaul operation, develop a list of tools needed for an overhaul and an estimate of the manhours needed to do an overhaul.

A decision has to be made about where the overhaul work is to be done. A 3000 horsepower diesel engine weighs approximately 207,000 pounds so it will be logical to do the overhaul on board ship. Maintenance analysis will determine who will do the overhaul work; the ship's crew or repair specialists from shore installations. If shore specialists are to be used, then missions have to be scheduled so the ship will be at the right location when overhaul work is done.

While analyzing the diesel generator for overhaul maintenance, the personnel relation to the equipment will be analyzed. Most likely, hoisting systems will be installed over the diesels to assist in disassembly of the heavy parts such as the cylinder head and the pistons. If the analysis is done early in the ship design it will be possible to include qualitative maintainability characteristics in the total design like the Design Work Study Program does.

A plan has to be made for phasing the operation of the diesels so that both diesels do not have to be overhauled at the same time. It would be logical to run one diesel a thousand hours before starting the other. Then diesel operation could be switched every week or after 168 hours of operation. One thousand hours of operation would occur after 42 days in a mission.

Maintenance plans of diesel generators have to consider all the ships of the same design using the equipment to assure that all repair parts are ordered at the same time. Appreciable savings in unit costs can be made by ordering the maximum number of repair parts at one time.

The maintenance analysis has to be done to assure that maintenance can be done, that repair parts will be available, that technical information is available for the technicians and that tools and test equipment will be available.

4.3 MAINTAINABILITY TASK ANALYSIS

A completed maintainability task analysis is shown to demonstrate the analysis of the steps in repairing a faulty control and indicator panel in a Test Station. The sequence starts with disassembly to gain access and isolating the defective part (Figure 8-37). Then in figure 8-38 the steps in making the repair are defined. This type of analysis provides the basic planning information necessary to provide the proper personnel, tools,

MAINTAINABILITY TASK ANALYSIS

SYSTEM: BMS TEST STATION

PART NUMBER/NOMENCLATURE: PANEL, CONTROL & INDICATOR / A1510-001 — T6888000

MA CONTROL NUMBER: T6888200

REQ NO	REQUIREMENT	CODE	OPERATING LEVEL	MTBF	TECHNICAL JUSTIFICATION	REMARKS
01	[illegible]	UP	2000 HOURS	1512	TROUBLESHOOTING OF THE CONTROL & INDICATOR PANEL TO THE PIECE PART LEVEL IS NECESSARY BEFORE CORRECTIVE ACTION CAN BE INITIATED.	△ INCLUDES WEIGHTED AVERAGE FOR "9---" TASKS. △ FREQ OF MAINT = 0.00135/OPERATING HOUR. REFER TO LOGIC FLOW DIAGRAM-SHT 2

REFERENCES: T6888000 REQ NO. 01

MAINT LVL AND TASK NO.	TASK DESCRIPTION	ELAPSED TIME (MINUTES)	CLASS/TASK FREQ	AFSC	MAN MINUTES (TOTAL)	TOTAL	TOOL NO. / TOOL NAME	TOOL QTY
[illegible]	GAIN ACCESS a. DISENGAGE SIX PANEL FASTENERS b. SWING PANEL OPEN	①	[illegible]	31350	010	010	58148-001 SCREWDRIVER	010
	WARNING DANGEROUS VOLTAGES PRESENT DURING TROUBLESHOOTING							
[illegible]	ISOLATE TO COLLAR (.00008)	①	[illegible]	31350	002	002		
[illegible]	ISOLATE TO RESOLVER (.00040)	①	0005	31350	005	005	A15006-001 MULTIMETER; A11820-001 OSCILLOSCOPE	005; 005
[illegible]	ISOLATE TO A.P.I. (.00032)	①	0004	31350	004	004	A15006-001 MULTIMETER	004
[illegible]	ISOLATE TO SWITCH S-9 (.00024)	①	0003	31350	003	003	A15006-001 MULTIMETER	003
[illegible]	ISOLATE TO SWITCH S-12 (.00032)	①	0004	31350	004	004	A15006-001 MULTIMETER	004
[illegible]	ISOLATE TO RESOLVER ADAPTER (.00008)	①	0001	31350	001	001		
[illegible]	ISOLATE TO DIAL (.00008)	①	0001	31350	001	001		
	REF T6888200 REQ NO. 02 REPAIR							

EXAMPLE

CHANGE NO. 2

TOTAL ELAPSED TIME/REQ'MT: 018 △

TOTAL MAN-MINUTES: 018 △ — TOTAL NO MEN: 001

SHEET 1 OF 1

PREPARED BY: T.R. SMITH

DATE: 24 APRIL 1964

MAINTAINABILITY TASK ANALYSIS

SYSTEM: BNS TEST STATION

PART NUMBER, NOMENCLATURE: A1510-001/PANEL, CONTROL & INDICATOR

NEXT ASSEMBLY: T6886000

7. MA CONTROL NUMBER: T6888200

3 RQD NO	4 REQUIREMENT	5 CODE	6 TECHNICAL JUSTIFICATION
02	REPAIR	UF	A FAULTY CONTROL & INDICATOR PANEL MUST BE REPAIRED TO RESTORE TEST STATION TO FULL OPERATIONAL CAPABILITY.
8 MTBF	9 OPERATING LIFE	10 REPL INT	
1512	2000 HOURS	⚠2	
11 REFERENCES			
T6888200 REQ. NO. 01			

7 REMARKS:
⚠1 FREQ. OF MAINT. = 0.00138/OPERATING HOUR.
⚠2 INCLUDES WEIGHTED AVERAGE FOR "9---" TASKS.

2 MAINT LEVEL AND TASK NO	13 TASK/DESCRIPTION	14 ELAPSED TIME - MINUTES	15 ELAPSED TIME TOTAL/TASK	16 JOB SPECIALTY OR RATING AFSC	17 BASIC SKILL	18 INTERMED SKILL	19 SUPER SKILL	20 TOTAL	21 QTY/ASSY	22 PART NO / 27 PART NAME	23 MAINT QTY FACTOR	24 SHELF LIFE	25 TOOL NO / 28 TOOL NAME	26 TOOL USE
0010	PREPARE FOR CORRECTIVE ACTION	1	002	31330	002			002						
	a. TURN OFF POWER TO TEST STATION BY OPENING CB's 1 & 2													
9020	REM & REPL COLLAR (.00008)	1	008	31330	008			008	01	540522-025 COLLAR	[illegible]	ND	58148-001 SCREWDRIVER	008
9030	REM & REPL RESOLVER (.00041)	1	004	31330	004			006	01	A1521I-0 RESOLVER	[illegible]	ND	58148-001 SCREWDRIVER	006
9040	REM & REPL A.P.I. (.00080)	1	006	31330	006			006	02	A1519T-001 API	[illegible]	[illegible]	58148-001 SCREWDRIVER	006
9050	REM & REPL SWITCH S-10 (.00029)	1	018	31330	018			018	01	15153-000 SWITCH, RVT	[illegible]	ND	58148-001 SCREWDRIVER; 71011-004 SOLDERING GUN	018; 018
9060	REM & REPL SWITCH S-12 (.00029)	1	025	31330	025			025	01	A1519I-002 SWITCH, RVT	[illegible]	ND	58148-001 SCREWDRIVER; 71011-004 SOLDERING GUN	025; 025
9070	REM & REPL RESOLVER ADAPTER (.00017)	1	010	31330	010			010		A1506-001 RES. ADAPT	[illegible]	ND		
9080	REM & REPL DIAL (.00003)	1	002	31330	002			002		B16999-TD DIAL	[illegible]	ND	58148-001 SCREWDRIVER	002
0090	CLOSE PANEL	1	011	31330	011			011					58148-001 SCREWDRIVER	011
	a. ENGAGE PANEL FASTENERS													
	b. TURN ON TEST STATION POWER BY CLOSING CB's 1 & 2													
	REF: T6888200 REQ. NO. 03 FUNCTIONAL TEST													

- EXAMPLE -

CHARGE NO.: 2

JOB SPEC - NO: 31330, 001

35 TOTAL ELAPSED TIME/REQ'MT: 024 ⚠2

36: 024 — 44: 001

39 TOTAL MAN-MINUTES: 024 ⚠2

49 TOTAL NO. MEN: 001

SHEET 1 OF 1

PREPARED BY: J. R. SMITH

DATE: 24 APRIL 1964

supply support and personnel training requirements for later use of the equipment aboard ship.

5. MAINTAINABILITY DEMONSTRATION

5.1 ELECTRONIC SYSTEMS

As with reliability or performance, a requirement for maintainability is unenforceable unless some means of verification is provided. For electronics equipment MIL M 23313A(2) provides a maintainability demonstration plan to be applied to a preproduction model before the start of production. The test consists of inducing failures in the equipment, requiring a technician to identify and repair the failure without prior knowledge of the failed item. For the test plan of Reference (2), twenty failures are selected in rough proportion to their probability of occurrence. The failed component is selected using random numbers or other unbiased techniques. The time for each step of the repair is measured and recorded. The time is adjusted for the experience level of the technician by a factor based on his years of experience.

When the twenty repairs have been completed, the evaluation is conducted as follows:

The acceptance criterion, log $MTTR_G \leq$ log ERT + 0.397(S), assures a probability of .95 of accepting an equipment or systems as a result of one test when the true geometric mean-time-to-repair is equal to the specified equipment repair time (that is, a probability of 0.05 of rejecting an equipment or system having a true $MTTR_G$ equal to the specified ERT). This was derived by using conventional methods for establishing acceptance criteria (Chapter 11). The conventional methods for determining acceptance based on the measured mean of a small sample, that is, sample size less than 30), and when the true standard deviation (σ) of the population can only be estimated, is to compare the measured mean with the desired mean using the expression:

$$t = \frac{(\bar{x} - \bar{x}_0)}{S} \sqrt{N-1} \qquad 8.2$$

where: $S = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{N}}$ or the standard deviation of the sample;

x = the sample or measured mean
x_o = the specified or desired mean
N = the sample size
x_i = the value of one measurement of the sample.

the decision to accept the product will be made when the test results give a value of t, as calculated from expression 8.2 numerically less than or equal to a value of t obtained from "Student's t" distribution tables at the established level (that is, 0.99, 0.95, 0.90, and so forth) of acceptance and the appropriate sample size. The "Student's t" distribution tables (for a single tailed area) give a value of t = 1.729 at the 0.95 acceptance level when the sample size is 20 (that is, 19 degrees of freedom.) The table for single tailed area is used since only values of $MTTR_G$ greater than the specified ERT are critical. An equipment with any value of $MTTR_G$ lower than the specified ERT is acceptable. To apply expression 8.2 to the maintainability test, let x_o = log ERT (specified), $\bar{x}$ = log $MTTR_G$ (measured), S = the measured standard deviation of the logarithms of the sample of measured repair time, and N = the sample size of 20. The measured $MTTR_G$ is then compared with the desired ERT by calculating the value of t using the expression below:

$$t = \frac{(\log MTTR_G - \log ERT)}{S}\sqrt{19} \qquad 8.3$$

The equipment under test can be accepted if the value of t calculated from expression 8.3 is equal to or less than +1.729 (the value of t from the "Student's t" distribution tables at an acceptance level of .95 when the sample size is 20). Therefore, the equipment should be accepted when:

$$\sqrt{19}\,\frac{(\log MTTR_G - \log ERT)}{S} \leq +1.729 \qquad 8.4$$

Upon rearranging and simplifying this expression, the acceptance criterion is obtained as shown below:

$$\log MTTR_G - \log ERT \leq \frac{1.729(S)}{\sqrt{19}}$$

$$\log MTTR_G \leq \log ERT + .397(S)$$

In the event the criterion is not met, the test shall be repeated. If, for the second test, the criterion is met, the maintainability requirement for the preproduction model will be considered to have been met. If, for the second test, the criterion is still not met, the equipment will be considered to have failed the maintainability requirements for the preproduction model.

Therefore, the combined probability of acceptance of an equipment or system with a true $MTTR_G$ equal to the specified ERT is 0.95 + 0.05 (0.95) or 0.9975. Thus, equipment of specification quality (that is, $MTTR_G$ = ERT) or better will almost certainly pass the combined test.

The test procedure is designed for producers risk of .0025 and consumers risk of .0975 based on the assumption of log normal distribution of times to repair and the specified ERT.

5.2 MECHANICAL SYSTEMS

Again the demonstration of compliance is necessary if assurance of the achievement of the requirement is to be obtained. While there is less evidence in mechanical repairs than in electronic systems to indicate that repair times are distributed log-normally, the underlying distribution can be estimated from the maintainability prediction data. The design of a test procedure for acceptance testing will be done in the manner discussed in Chapter 11. Again, where a test proposed by a contractor is being reviewed, or a test being proposed to a contractor, obtain the assistance of a qualified statistician.

6. APPLICATIONS TO CURRENT WORK

6.1 DEFINITION OF REQUIREMENTS

We have just run through a multitude of pages in an attempt to show you the basic ingredients of Maintainability, how it gets into the systems development process and how it relates to other design parameters. Most of you are doing engineering work on new or modified subsystems which eventually will be installed in existing ships. You are probably aware of the present operational support problems which now exist in similar equipment and are desirous to get maintainability built-in to new specifications on an equal level.

There are two items which have to be answered: how much Maintainability is needed, and how sure do you want to be that your requirement is met? To answer the former, it is necessary first to know the mission of the equipment, i.e., how often is it demanded for operation, who will operate it and what is its environment. Second, the amount of Maintainability needed depends on cost of achieving various levels of Maintainability versus cost savings through reduced down time. The only reason for this relatively new discipline is reduced costs with an attending increase in system effectiveness.

Next, what confidence is wanted that the MTTR will be met? This again relates to cost. It also relates to the sensitivity of Maintainability of individual elements to the overall system availability. Defining requirements becomes of question of how much it costs to produce versus how much it costs to use for various levels of availability.

6.2 CONTRACTING FOR MAINTAINABILITY

In order that the contractor understands fully the BUSHIPS need for Maintainability it must be clearly and explicitly defined in contracts for new equipment or in follow-on contracts for modifications of existing equipment. Specifically, the following items should be considered for inclusion in a hardware contract:

a. Quantified MTTR or availability goals for consideration by the contractor: The word "consideration" is used since it is desirable to give the contractor some latitude in order that he may analyze tentative goals and perhaps submit a recommendation to BUSHIPS as to how goals could be changed for reduced costs. (But <u>do</u> specify a maximum allowable down time or ERT where appropriate).

b. Tell the contractor how much you expect Maintainability to be weighted in his total design effort against other technical disciplines such as the various aspects of performance, reliability, etc.

c. If contract is of the CPIF type, specify how incentive fees will be paid on the basis of the contractors performance in the maintainability portion of the Dependability Plan.

d. Tell the contractor what special maintainability problem areas, if any, to investigate.

e. Supply in the contract specification, other applicable documents such as the general specification MIL M 23313.

Tell the contractor which portions of the specifications are applicable to your particular subsystem. Delineate the maintenance analysis forms he must use and the frequency of reporting results.

7. REFERENCES

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4. Think System, Don't Think Hardware, Jerome E. Levy, SAE, ASME, AIAA Conference Proceedings Third Annual Conference on Aerospace Reliability and Maintainability, Washington, D. C., June 29, 1964, Society of Automotive Engineers, Inc.

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Chapter 9

DATA ACQUISITION

Chapter 9

DATA ACQUISITION

In the development of a system or equipment a large amount of data is collected and used. The data adds to the objective evidence used by the designer in making decisions about the design, by the inspector in making decisions about acceptance and the program manager in making decisions concerning the program. In this chapter we will attempt to develop two areas:

(1) The interpretation of data; that is, the recognition that a particular group of data is a sample drawn from a larger population, and that inferences can be made about the characteristics of that population from the sample.

(2) The generation or collection of data, useful sources, limitations on their validity and practical value of use data

In the design, procurement, testing and operational use of an equipment there is an infinite variation in characteristics. No two equipments are ever the same. If you put two "identical" equipments on test they won't fail at the same time. The differences are each, in most cases, minor - a half a thousandth here in clearance, a tenth of an inch-pound in balance, an almost undetectable difference in roughness of surface funish, and so forth. Within crude limits, the equipments are identical. With more exact measurements, a difference can be found.

Because of this variability from sample to sample, the interpretation of the data depends on the branch of scientific method called statistics.

The real utility of sample data from tests of individual units lies in the capability of making statements about the population from which the sample was taken. Mistakes can be made when you try to infer a general rule (make a statement about the population parameters) from a specific case (the sample data). Statistical theory is the only method now known that permits some degree of control to prevent such mistakes.

1. THE POPULATION

Before any specific functions are discussed, it is important to state the usual nature of the statistical problem in order to explain how one should view the formulas and curves to be presented. Collected data received from any testing or surveillance program should be viewed as information to be used in guessing what will happen in the future -- that is, in prediction. Of course, there is an element of historical interest in knowing what did happen just for the sake of knowledge itself. The real payoff, however, lies in using the data as a sample from some population, and the job at hand is one of describing this population from some of the characteristics of the sample data. For example, one would like to be able to take field data on failures in a specific weapons system and write the formula for the failure density of all future failure experience which will be met with this same system and even with improved versions of the system, using adjustment for the system modifications.

The moral of this view is that field data constitutes a sample, that random sampling peculiarities must be smoothed out, that population density parameters must be estimated, that the estimation errors must themselves be estimated, and -- what is even more difficult -- that the very nature of the population density must be estimated. To achieve these ends, it is necessary to learn as much as possible about the possible population density functions, and especially what kind of results we can expect when samples are drawn, the data are studied, and we attempt to go from data backward to the population itself. It is also important to know what types of population densities are produced from any given set of engineering conditions. This implies the necessity for developing probability models, or going from a set of assumed engineering characteristics to a population density.

It is customary, even necessary, in statistical analysis to develop from the physical engineering principles the nature of the underlying distribution. The sample of data is then tested against the assumed distribution.

The usual parameter of interest in reliability is the distribution of times to failure, called the probability distribution function or failure density function. The failure density function may be discrete, that is, only certain (integral) values may occur, as in tests of an explosive squib. Success or failure will occur on any trial, time not being considered. Or it may be continuous, any value of time to failure being possible.

In the analysis of parameters of populations the following distributions have been found to be useful.

1.1 BINOMIAL DISTRIBUTION

The Binomial distribution arises from a series of Bernoulli trials.

A Bernoulli sequence of trials is defined as sequence of experiments satisfying the following conditions:

1. For each experiment, the result is either success or failure;

2. The probability of success is the same for every experiment;

3. Each trial is independent of all others.

The binomial failure density function is

$$f(r) = \binom{n}{r} p^{n-r} q^{r} = \frac{n!}{(n-r)!\ r!} p^{n-r} q^{r}$$

where

n	is the number of trials
r	is the number of failures
p	is the probability of success
$q=(1-p)$	is the probability of failure.

Hence $f(r)$ is the probability of exactly r failures out of n when the probability of a success is p.

The probability of r or more failures out of n Bernoulli trials is given by:

$$F(r) = \sum_{i=r}^{n} \binom{n}{i} p^{n-i} q^{i}$$

$F(r)$ is the cumulative distribution function, and may be interpreted as the probability of r or more failures out of n trials.

Since the equipment must either succeed or fail, the sum of the probabilities equals unity.

The probability of success, $R(r)$, where success is defined as <u>less than</u> r failures, is the complement of $F(r)$, that is:

$$R(r) = 1 - F(r) = 1 - \sum_{i=r}^{n} \binom{n}{i} p^{n-i} q^{i}$$

We can define the expected number of successes, E(s) as the average or mean value of the distribution. This value is the product of the number of trials and the probability of success on each individual trial. That is:

$$E(s) = np$$

and the variance of s (number of successes) is:

$$\mathrm{Var}\ (s) = \sigma_s^2 = npq$$

Hence, the standard deviation σ_s is:

$$\sigma_s = \sqrt{npq}$$

The independent parameter of the Binomial is p, the probability of success. The properties of the distribution are shown in Figure 9-6.

Basically, the Binomial distribution is utilized in cases where the equipment operates in definite cycles such as an on-off switch, or in cases where the cycle is some minutes in length but involves varying stresses and operation and; hence, varying probability of failure from minute to minute, provided each trial is independent, success or failure on any individual trial not affecting the results of prior or subsequent trials, and each overall trial has the same probability of success. An example would be a missile flight. Such flights are programmed so that each flight is a duplicate of the others. The same stress-time cycle is imposed.

1.2 EXPONENTIAL DISTRIBUTION

The Exponential failure density function,

$$f(t) = \lambda e^{-\lambda t}$$

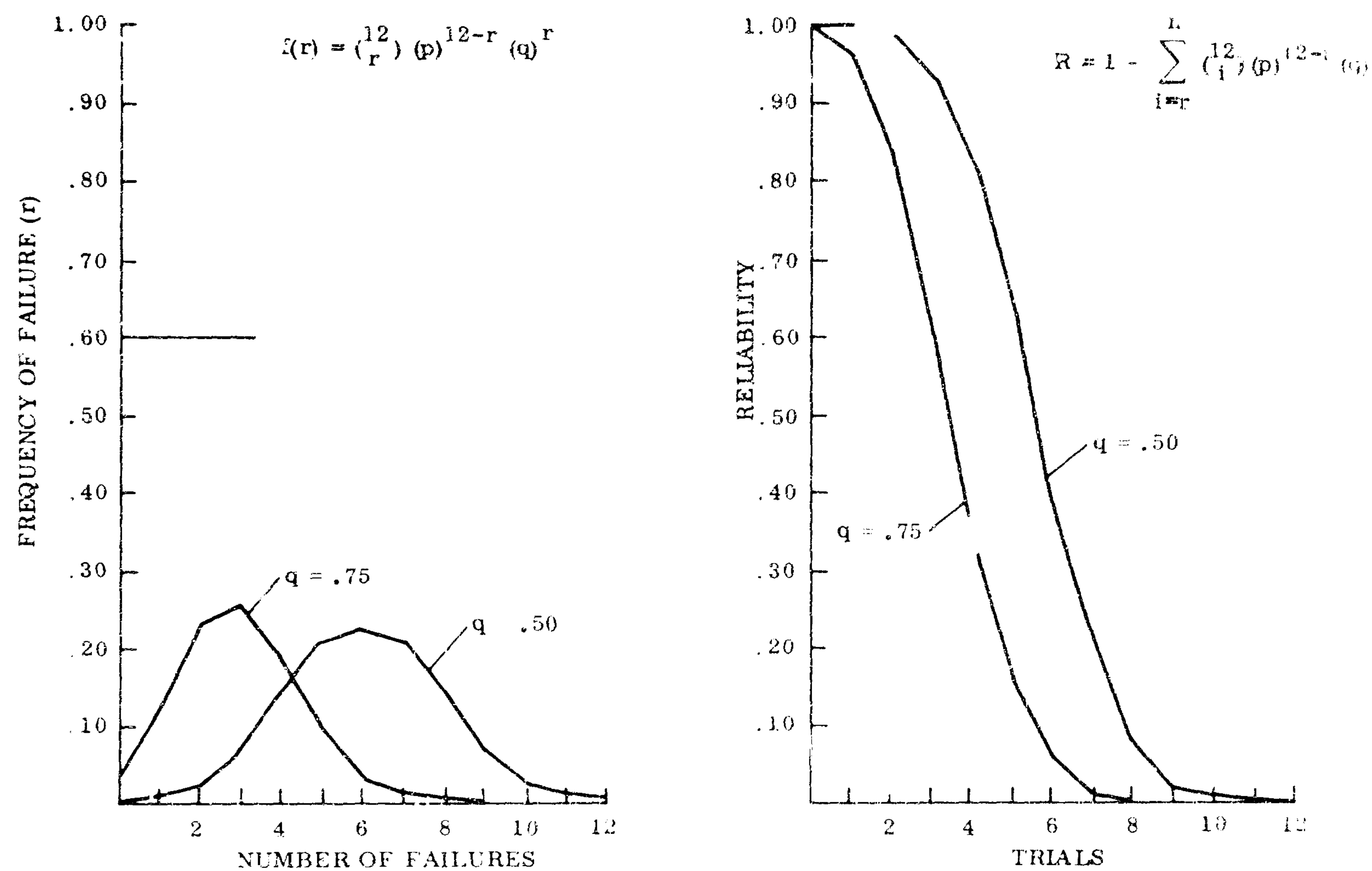
λ = mean failure rate

t = time under consideration

is widely used. The distribution is a special case of both the Weibull and the Gamma distributions.

The equation above is the one most usually thought of when the Exponential distribution is spoken of. This is, of course, the

BINOMIAL DISTRIBUTION FUNCTION



Exponential distribution of failures over time. Since R(t) is the probability of no failure prior to time t, then:

$$F(t) = 1 - R(t)$$

is the probability of one or more failures in time t,

where: $R(t) = e^{-\lambda t}$

is the probability of operating successfully for a time, t.

The Exponential distribution is characterized by a constant failure rate and MTBF (= $1/\lambda$).

The distribution is valuable if properly used. It has the advantage of:

1. Single easily estimated parameter.

2. Mathematically easy to work with.

3. Applicable fairly widely.

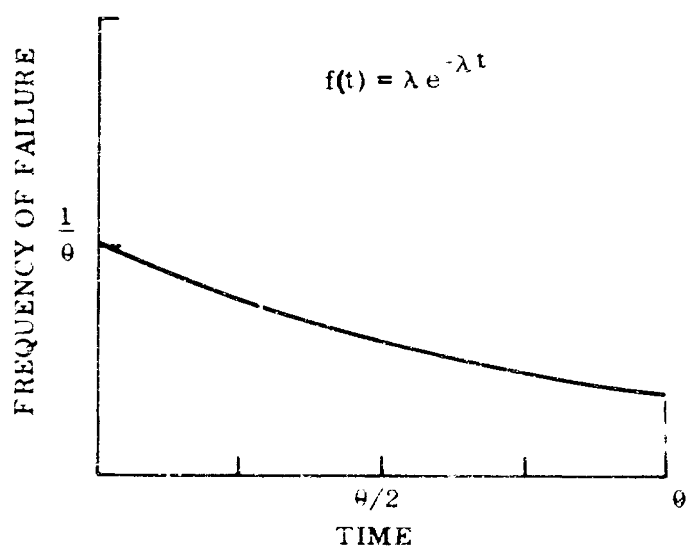
4. Is additive - that is, the sum of a number of independent exponentially distributed variables is exponentially distributed.

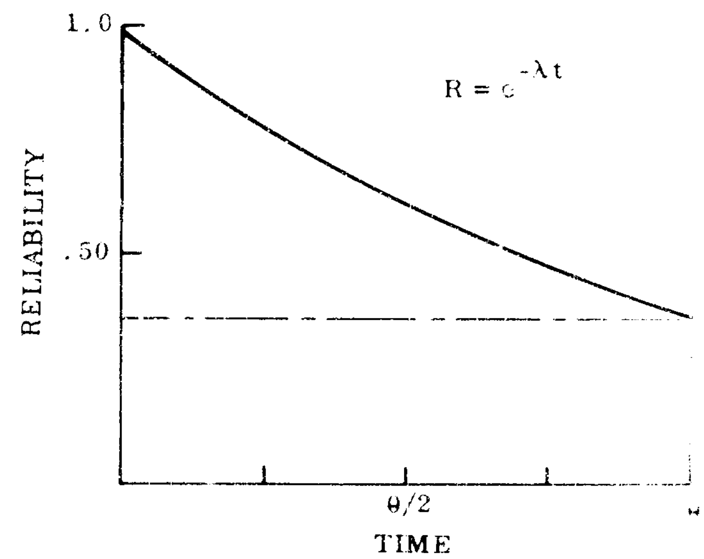
Care must be taken to insure its limitations are not exceeded. It arises from a Poisson process and is applicable only where such a process exists. Its parameter is the mean failure rate. The reciprocal is the mean time between failures (MTBF) and is often used as a reliability goal. Care must be taken in interpretation if this is done. If a certain model of equipment has an exponential distribution of life lengths and achieves a MTBF of 500 hours, this does not mean that most equipments of this model will run about 500 hours before failing. In fact, 63 percent will fail prior to this time. Since the probability of success is defined as $R = e^{-\lambda t}$ where λt equals 1 (that is t = MTBF and $\lambda t = \frac{t}{MTBF} = 1$). The value of e^{-1} is 0.368, or the reliability of the unit to time = MTBF is about 37%. Figure 9-8 displays the Exponential Functions.

1.3 POISSON DISTRIBUTION

The Poisson distribution arises from a very large number of trials each with a very small probability of occurrence. The distribution is discrete, referring to failures per numbers of trials

EXPONENTIAL DISTRIBUTION





rather than time to failure. As in the case of the binomial, the sum of probabilities equals unity. The Poisson failure density function:

$$f(r) = \frac{e^{-np}(np)^r}{r!}$$

where

r = number of failures

n = number of trials

p = probability of failure on any one trial.

We use p as the probability of failure in the Poisson distribution (instead of probability of success as in the binomial) because we wish to use the distribution in reliability areas in which the probability of failure is a small number. The product np should be relatively constant.

The probability of r or less failures in n trials

$$F(r) = \sum_{i=0}^{r} \frac{(np)^i e^{-np}}{i!}$$

The reliability $R = 1 - F(r) = \sum_{i=r}^{\infty} \frac{(np)^i e^{-np}}{i!}$

We can think of a test period of 10 hours being broken up into milli-seconds. Each milli-second is an independent trial (assuming instantaneous repair to any failures that occur). There are $r = 36 \times 10^6$ trials, each with a small probability of failure. If the failure rate of the equipment is $\lambda = .001$ failures per hour, the probability of failure on one (milli-second) trial $p = .001 \times \frac{1}{36 \times 10^6}$ The product $np = .01$

The distribution is also useful in the consideration of a large population of parts, each with a small probability of failure. If the product np is constant and is the expected number of failures on a single trial (which in the case of the exponential distribution is λt) then the function F(r) gives the probability of having r or more failures on the trial. The probability of having one or more failures on a given trial is the exponential distribution function

$$F(t) = \int_0^t \lambda t\ e^{-\lambda t}$$

and the probability of success on the trial is

$$R(t) = e^{-\lambda t}$$

Figure 9-11 displays the Poisson function.

1.4 NORMAL DISTRIBUTION

The Normal failure density function is

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \quad e^{-(x-\mu)^2/2\sigma^2} = n(\mu,\sigma)$$

where σ^2 is the variance, μ is the MTBF and x is the observed time to failure.

The cumulative distribution function is:

$$F(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \int_0^t e^{-(x-\mu)^2} dx = 1 - R(x)$$

The reliability distribution is, of course:

$$R(x) = 1 - F(x)$$

The Normal is useful in reliability mathematics for two reasons:

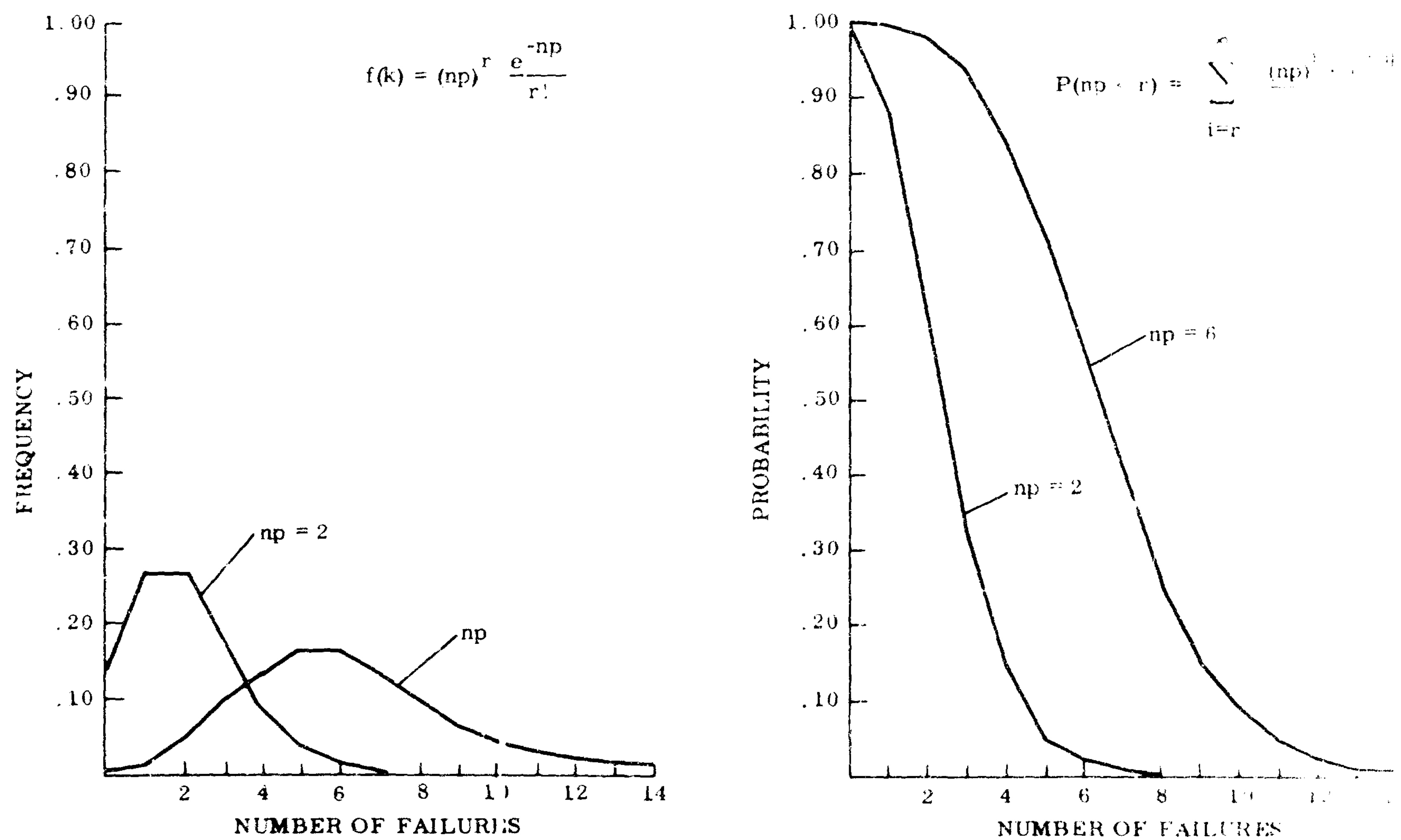
1. Wide applicability due to the central limit theorem.

2. Provides a direct description of the distribution of times to failure under certain conditions.

The distribution is continuous and is a two parameter distribution. The mean and variance are particularly meaningful, since it is a symmetric distribution. The major direct area of reliability application is in describing the distribution of wearout failures. Considerable empirical evidence has shown that in purely mechanical assemblies that this is a good approximation.

The distribution is, however, easy to work with and has several valuable properties. The simple transformation,

POISSON DISTRIBUTION FUNCTION



$$z = \frac{x - \mu}{\sigma}$$

transforms any Normal variable x to the so called standardized Normal variable z which has a zero mean and unit variance. The frequency and the cumulative distributions of the standard Normal variable are tabled in nearly every statistical text. The Normal distribution also has the additive property. Figure 9-13 summarizes the characteristics of the Normal distribution.

1.5 LOGARITHMIC NORMAL DISTRIBUTION

The three parameter log normal frequency function is:

$$f(t) = \frac{1}{\sigma(t-\omega)\sqrt{2\pi}} \exp\left[\frac{-(\ln(x-\omega)-\mu^2}{2\sigma^2}\right]$$

$$t > \omega$$

$$\omega \geq o \geq t$$

where μ is the mean of log t

σ^2 is the variance of log t

ω is the location (threshold) parameter

The cumulative function is then

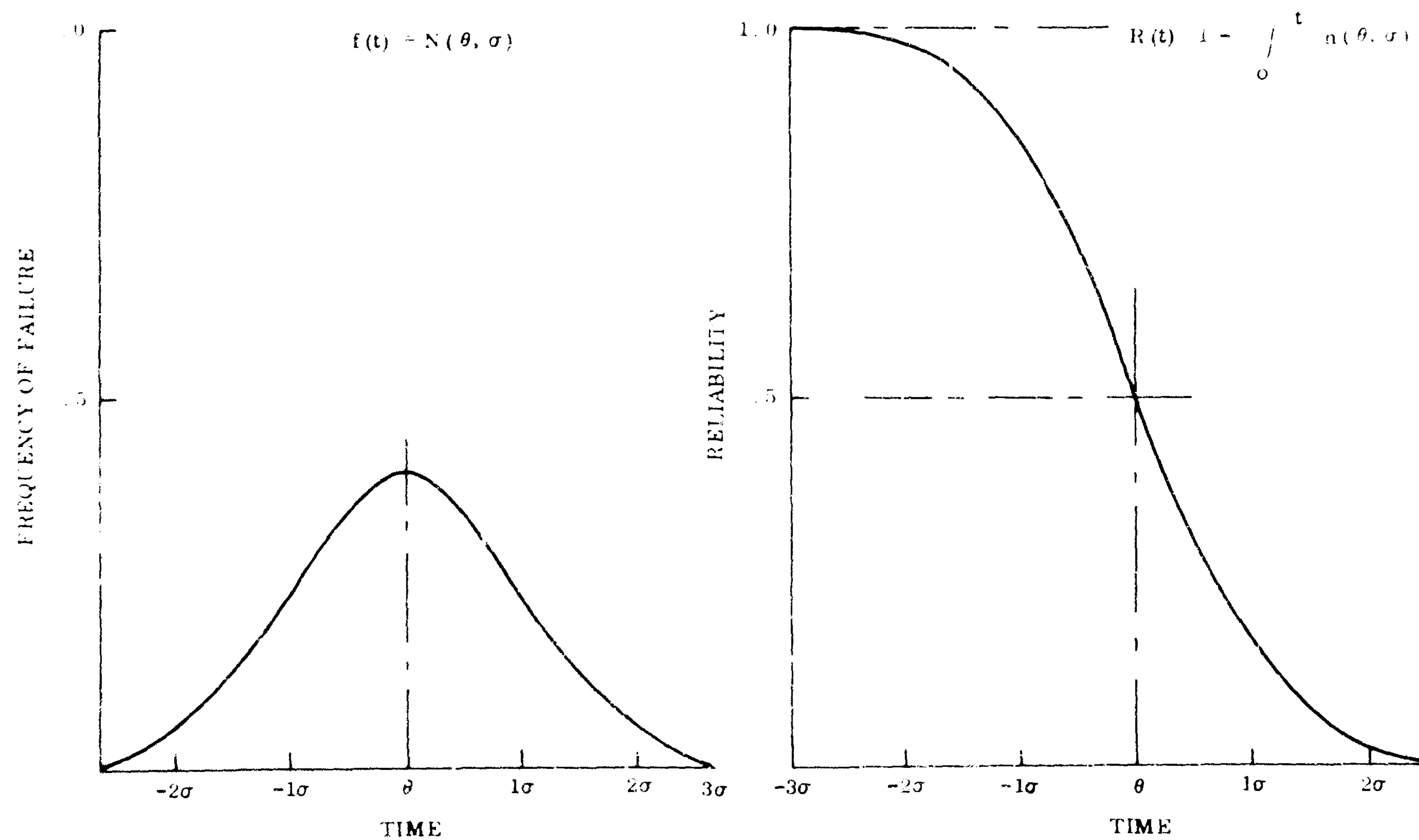
$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^t \frac{1}{x-\omega} \exp\left[\frac{-(\ln(x-\omega)-\mu)^2}{2\sigma^2}\right] dx$$

$$R(t) = 1 - F(t)$$

The log-normal distribution is a transformation of the Normal distribution in which logarithm of the time is used as the variable, instead of the time. A log normal distribution plotted on semi-logarithmic paper would appear a normal curve.

It may be shown that the Log Normal distribution applies to situations in which several independent factors all exert an influence on the final outcome of a given event not in a simple additive fashion but rather according to (1) the magnitude of the factor and (2) the importance of the event at the time in which the particular factor is applied. The distribution has been

NORMAL DISTRIBUTION FUNCTION



found to be representative of many cases of distributions of times to repair. It is used in prediction and demonstration of mean times to repair in MIL-M-23313 for example. (Figure 9-15 shows this distribution).

1.6 GAMMA DISTRIBUTION

The Gamma failure density function can be expressed as

$$f(t) = \frac{1}{\alpha!\ \beta^{\alpha+1}}\ t^{\alpha}\ e^{-\frac{t}{\beta}}$$

$$t \geq 0$$

$$\beta > 0$$

$$\alpha > -1$$

where t is time to failure

α is the shape parameter

β is the scale parameter

The failure rate is constant, increasing and decreasing accordingly as

$$\alpha = 0,\ \alpha > 0,\ \alpha < 0.$$

The cumulative density function is not expressable in elementary mathematical terms except when α is a positive integer, but may be found tabulated in tables of incomplete Gamma functions.

It has the form:

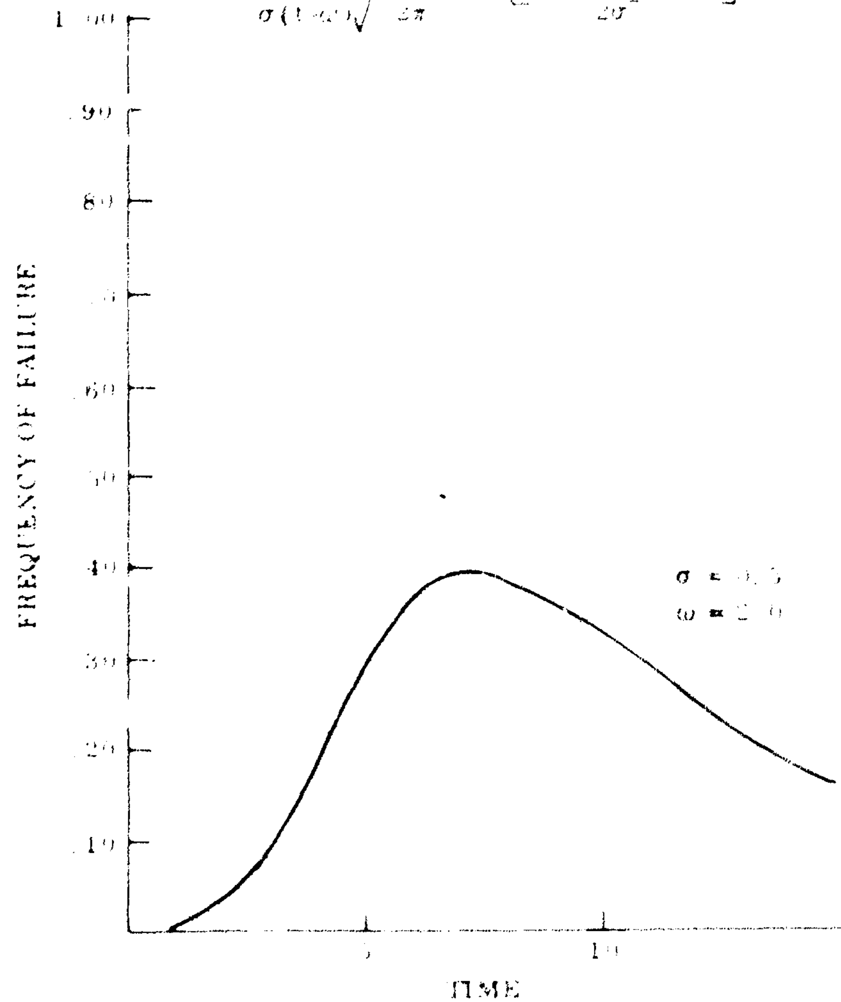
$$F(t) = \int_0^t \frac{1}{\alpha!\ \beta^{\alpha+1}}\ x^{\alpha}\ e^{-\frac{x}{\beta}}\ dx$$

The Gamma family of distributions is a flexible, two-parameter family of distributions which contains the Exponential distribution as a special case when $\alpha = 0$. β then becomes the MTBF.

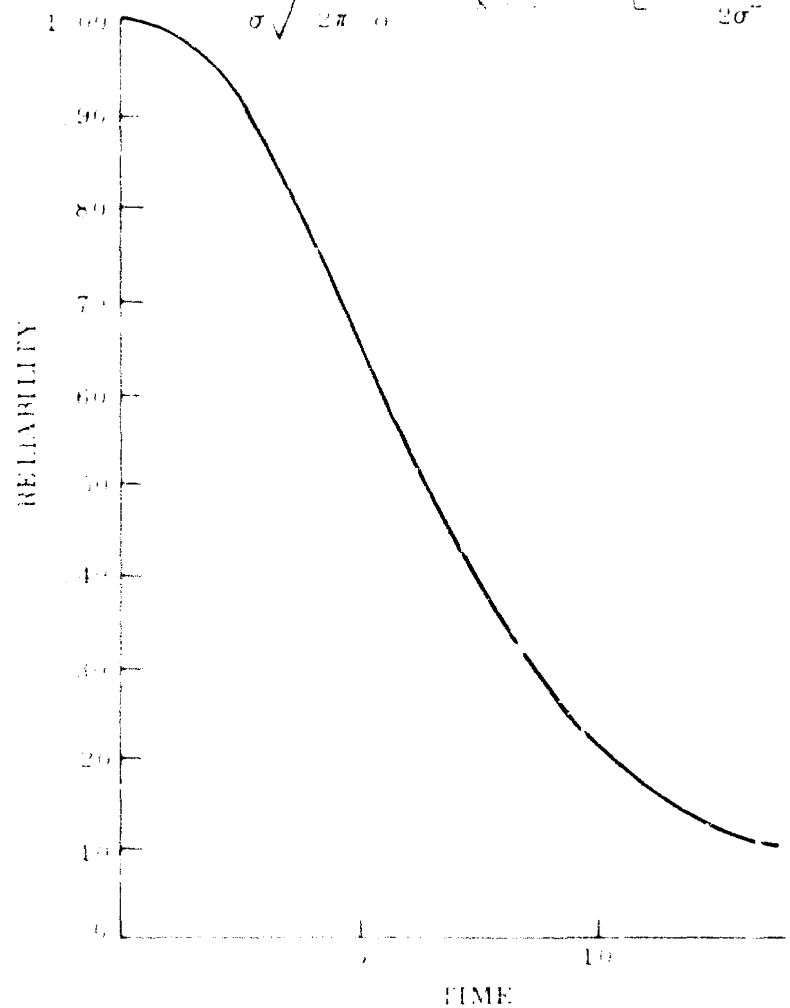
Both the Gamma and the Poisson distribution describe the phenomena arising from Poisson Process. The Poisson distribution is that of the discrete number of events (x) of a given type from n trials. The Gamma distribution is that of times to failure and is, hence, continuous over the time axis.

LOG-NORMAL DISTRIBUTION

$$f(t) = \frac{1}{\sigma(t-\gamma)\sqrt{2\pi}} \exp\left[\frac{-(\ln(t-\gamma)-\mu)^2}{2\sigma^2}\right]$$



$$R(t) = 1 - \frac{1}{\sigma\sqrt{2\pi}} \int_0^t \frac{1}{x-\gamma} \exp\left[\frac{-(\ln(x-\gamma)-\mu)^2}{2\sigma^2}\right] dx$$



The Gamma distribution will describe varying failure modes or combinations thereof. The distribution will become Exponential when heterogeneity exists among the failure modes. As heterogeneity decreases, the distribution approaches the Normal. Figure 9-17 displays the variation in the frequency for varying parameter values.

1.7 WEIBULL DISTRIBUTION

The Weibull distribution is characterized by the failure density function.

$$f(x) = \frac{\beta}{\alpha} (x-\omega)^{\beta-1} \exp\left[\frac{-(x-\omega)^{\beta}}{\alpha}\right]$$

for

$\omega \leq x < \infty$

$\alpha > 0$

$\beta > 0$

and $f(x) = 0$ for $x < \omega$

This yields the survival (or reliability) function

$$R(x) = \exp\left[-\frac{(x-\omega)^{\beta}}{\alpha}\right]$$

where the cumulative distribution:

$$F(x) = 1-e^{-\frac{(x-\omega)^{\beta}}{\alpha}}$$

The Exponential case oc urs when $\beta = 1$; α then is the MTBF. The Normal distribution is approximated when $\beta \geq 3$, in which case

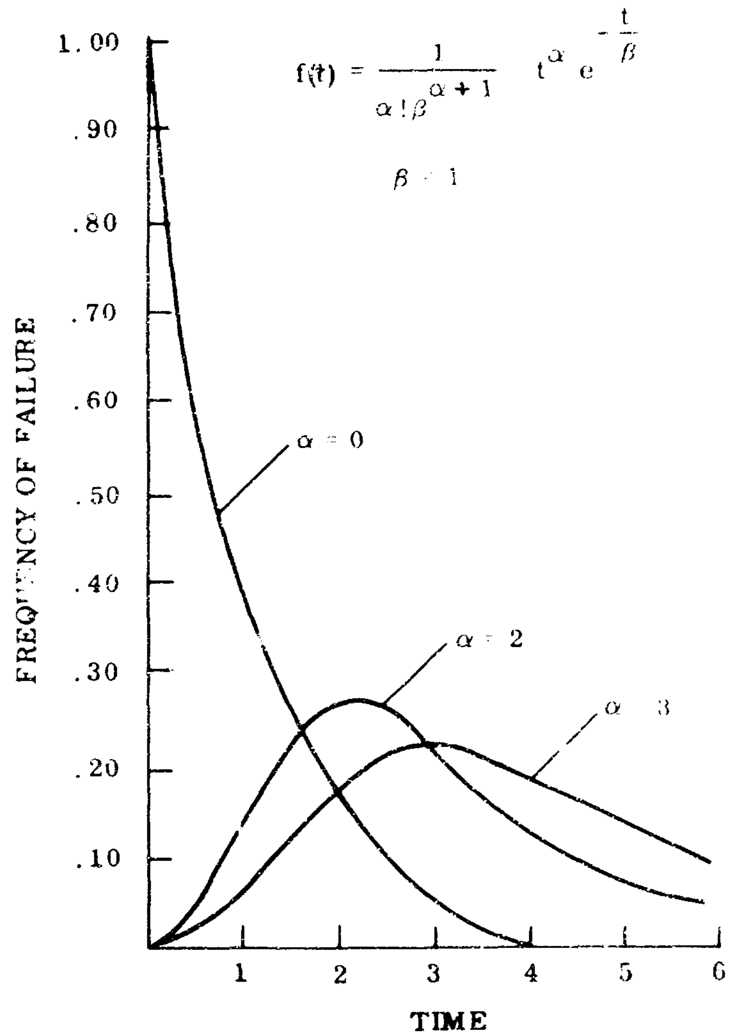
$$\mu = \omega + (\alpha)^{1/\beta}(1 + \frac{1}{\beta} \text{ and}$$

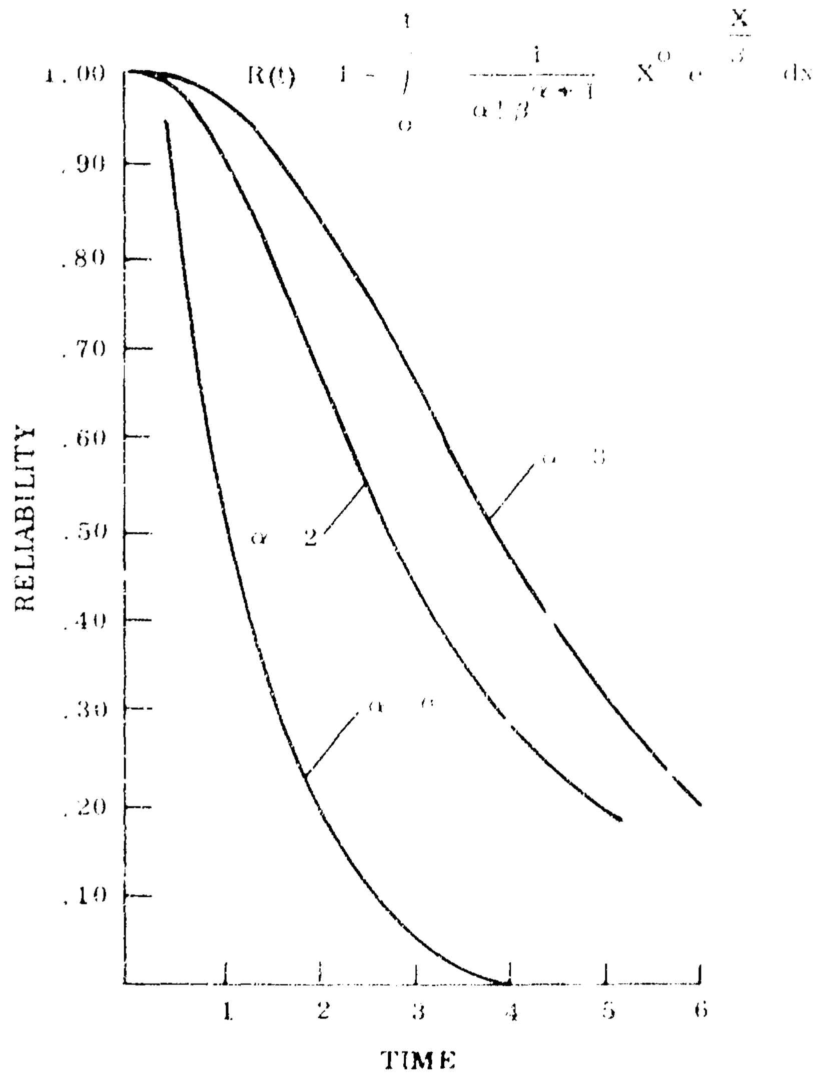
$$\sigma = (\alpha)^{1/\beta} \sqrt{(\tfrac{2}{\beta})! - \left[(\tfrac{1}{\beta})!\right]^2}$$

The effect of the three parameters is as follows:

$\underline{\beta}$ is the shape parameter, and determines the basic configuration

GAMMA DISTRIBUTION FUNCTIONS





of the frequency function.

$\underline{\omega}$ is the location parameter, and determines the point of origin of the curve,

$\underline{\alpha}$ is the scale parameter. The real positive βth root of α determines the dispersion of the frequency function about the mean.

The frequency function of several contributing failure modes can be represented as a composite Weibull frequency function such as:

$$F(x) = \frac{1}{2} \quad \frac{\beta_1}{\alpha_1} (x - \omega_1)^{\beta_1 - 1} \exp\left[\frac{-(x-\omega_1)^{\beta}}{\alpha_1}\right] + \frac{\beta_2}{2\alpha_2}(x-\omega_2)^{\beta_2 - 1} \exp\left[\frac{-(x-\omega_2)^{\beta_2}}{\alpha_2}\right]$$

This can be approximated by the function

$$f(x) = \frac{\beta_1}{2\alpha_1} \; x^{\beta_1 - 1} \exp\left[\frac{-x^{\beta_1}}{\alpha_1}\right] \text{ for } 0 \leq x < \alpha$$

$$= \frac{\beta_2}{2\alpha_2} (x-\omega)^{\beta_2 - 1} \exp\left[\frac{-(x-\omega)^{\beta_2}}{\alpha_2}\right] \text{ for } \alpha \leq x < \infty.$$

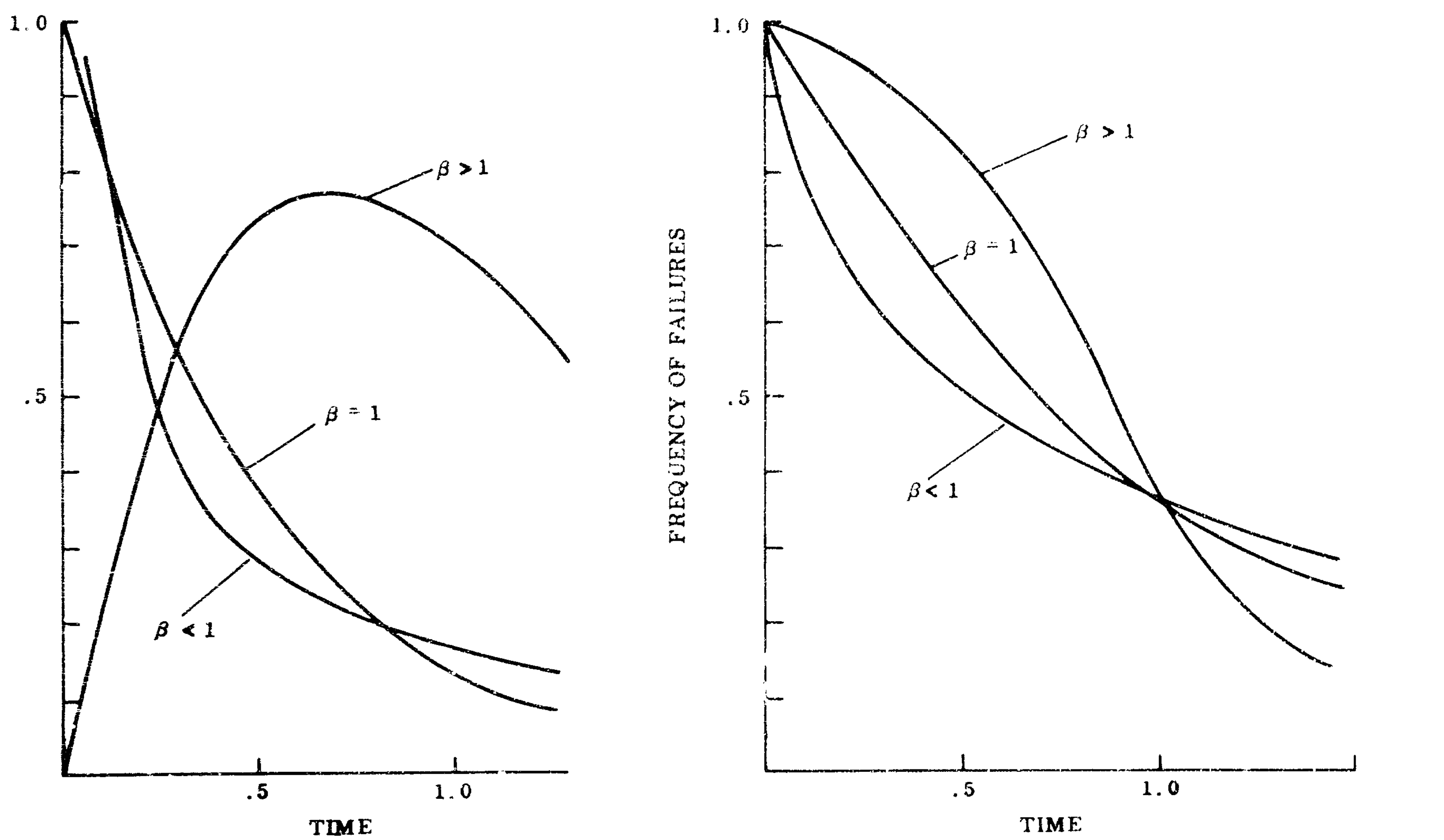
As can be seen, the Weibull is essentially a three parameter although ω, the location parameter (more appropriately, the delay parameter in reliability studies) is sometimes set equal to zero, and, thus, only two parameters remain to be estimated. This is not generally advisable, however, and the real flexibility of the Weibull distribution arises from the judicious use of all three parameters. The β parameter is the most powerful of the three, in a sense, since it controls the general shape of the curve and, thus, is the variable which permits that such a wide variety of curve types are included within the Weibull family. The α is a scale parameter which plays essentially the same role as σ in the Normal Distribution. The characteristics of Weibull distribution are described in Figure 9-19. Special paper developed for graphical solution to the Weibull parameters is available.

2. ACQUISITION OF DATA

2.1 NATURE OF FAILURES

The prediction or assessment of reliability is actually an eval-

WEIBULL DISTRIBUTION FUNCTIONS



uation of unreliability. It is the rate at which failures occur that we use for the measure of unreliability. The nature and underlying cause of failures must be identified and corrected to improve reliability. Reliability data consist of reports of failures and reports of duration of successful operation of the monitored equipment.

2.2 USES OF RELIABILITY DATA

Reliability data is used for three main purposes:

(a) To verify that the equipment is meeting its reliability requirements.

(b) To discover deficiencies in the equipment to provide bases for corrective action.

(c) To establish failure histories for comparison and for use in prediction.

Reliability data can also be useful in providing information about logistics, maintenance, and operations. The data can provide a good estimate of spare parts requirements. With respect to maintenance, reliability data make it possible to estimate the degradation and wear-out characteristics of parts and components. From this information, not only can effective preventive maintenance routines to control frequent trouble areas be developed, but also an estimate can be obtained of the number of maintenance man-hours required to assure a desired level of reliability.

2.3 VALIDITY OF DATA

It is important that the data be factual so that a high degree of credence may be placed in the conclusions derived from it. Incomplete and inaccurate reporting will inevitably lead to either complete loss of confidence in the data or to incorrect conclusions and hence incorrect decisions and actions based on the conclusions.

To assure that the information is valid requires that the methods and procedures applicable to the collection of the data be clearly defined. The personnel responsible for the data collection should be carefully selected and adequately trained not only in the methods and procedures of reporting, but also in the analysis of the data and the uses to which it will be put to enable intelligent and responsive reporting.

2.4 FACTORS OF IMPORTANCE IN REPORTING

Reports of failures should contain as a minimum:

(a) Time and date failure occurred.

(b) Location (Ship or Station).

(c) Identification of failed part or assembly by name, stock number and serial number where appropriate.

(d) Identification of higher level of assembly in which part or assembly failed by name, stock number or designation (as AN/SRR-13) and serial number.

(e) Symptoms or nature of the failure.

(f) Cause of failure, including causes such as operator error, result of another part failure (secondary failure), use beyond normal life expectancy, extreme environment (temperature, shock, etc.).

(g) Duration of operating time since last failure (computed from operating log).

(h) Circumstances surrounding the failure, with particular reference to any abnormalities noticed.

Entries in the equipment operating log will be used to establish or verify mean life (meantime between failures) of the equipment reported on. It should also be used to verify the use of the distribution of times to failure assumed in predictions or assessment of reliability parameters. As was discussed in Chapter 5, the exponential distribution of times to failure is normally assumed. Data indicating that certain parts or assemblies follow a Weibull or normal distribution with a typical wear-out or end of life characteristic will permit the establishment of realistic replacement schedules, with consequent improvement of reliability. Equipment operating logs should include, in addition to the identification data (ship or station, period covered, equipment designator, manufacturer, etc.):

(a) Recorded operating time prior to the start of the period (e.g., reading of installed time recording device).

(b) Duration of each operation of the equipment during the period, with purpose for which operated, abnormal environments and reason for discontinuing operation (such as failure, end of exercise, test completed, etc.)

(c) Length of time and manhours expended in maintenance (preventive or corrective), including reasons for maintenance, if not otherwise clearly indicated.

Field or use data acquired through failure reports and operating logs, while useful, cannot be termed conclusive. The data collected is usually incomplete, inconsistent, and inaccurate. The influence of intangibles, such as the variation in capability of operating personnel, or procedures used in maintenance and trouble-shooting, and the hesitancy of some personnel to admit errors when they can be hidden, confuse the data and make intelligent interpretation of the data difficult.

2.5 METHODS OF GATHERING RELIABILITY DATA -- FIELD DATA

There are two usual methods of gathering data: (a) at random from various installations or (b) on the basis of controlled programs using data from units functioning under operational conditions in accordance with a fixed routine.

Experience has shown that it is usually more advantageous to gather data by sampling techniques, because they are more rapid and less costly to the customer. However, sampling experiments cannot always be arranged, and difficulty has been encountered even when the government is the customer. Other methods, such as simulating field conditions in a laboratory and calculating the resultant reliability, or determining the failure rates of parts or components under simulated conditions of operation and calculating the system reliability, can be used. Simulated experiments, if performed properly, can provide an estimate of operational reliability, but it must be borne in mind that the methods used for simulating actual field conditions are at best a guess. Statistically designed experiments should be developed with the assistance of a completent statistician to improve the efficiency of the experiment. There are no good substitutes for the actual thing. Nevertheless, in some instances, the results obtained by simulation methods have often been proven to be more realistic than those based on actual field data gathered through uncontrolled programs. Field failure data obtained through a controlled program would, however, be superior to laboratory data because the former reflect actual operational conditions. The factors to be considered in choosing the type of program are (a) the degree of assurance required that the data obtained reflect an accurate picture of equipment reliability, (b) the amount of data required, (c) the period of time over which the data must be accumulated, and (d) the relative costs of various programs. When time permits, a controlled field program or a field and laboratory combination program should be used.

2.6 BUSHIPS DATA SYSTEMS

2.6.1 Electronic Failure Reporting System: Since August 1961, all active ships and shore stations furnish the Bureau with two reports (1):

(a) NAVSHIPS 4855, Electronic Equipment Operating Log;

(b) DD787 (PROPOSED) (Report BuShips 10550-1) Electronic Equipment Failure/Replacement Report.

Equipment failures are due to failures of integral parts, units or plug-in assemblies. The combined equipment/part failure report concept allows for the determination of accurate data essential to reliability, maintainability and availability figures of merit. It should be emphasized however, that no useful part data is sacrificed to obtain these figures of merit. An important feature of this program is the limiting of reports only to selected priority equipments. Reporting requirements have been eliminated for obsolete and obsolescent equipment. This in itself improves the paper workload as compared to the previous requirements of reporting on all equipments.

The two forms have been designed to provide the basic data necessary for the accurate calculation of reliability and maintainability figures of merit, such as the following: (a) Mean-Time-Between-Failures, (b) Mean-Time-To-Repair, (c) Down-Time, (d) Availability, (e) Failure rates and (f) Replacement (consumption) rates. In addition, the Failure/Replacement Report form provides the necessary identification data and conditions of failure information necessary for comprehensive engineering analyses of high failure rate items. The majority of Failure/Replacement and operational time data to be processed and analyzed in the BUSHIPS Failure Reporting/Analysis Program will be initiated and submitted by Navy Technicians. The success or failure of this program will therefore, be dependent upon the extent to which the technicans are motivated to provide as complete and accurate data as is possible. In the development of the new reporting forms and instructions, all aspects were considered from the technician's point of view to determine those factors that would assist in motivating him to provide the quality of reporting essential to the program's success.

Provisions have been incorporated into the new Failure/Replacement Report form to allow for:

1. Reporting plug-in assembly failures and repairs.

2. Reporting of failures or replacements in units which are auxiliary to, but not part of, equipment.

3. Reporting failures or replacements identified by either the unit or block numbering system of reference designations, (see MIL-STD-16).

4. Better identification of primary part failures (the particular part of a cluster of part failures, primarily responsible for an equipment failure, i.e., a shorted capacitor (primary) which caused burned out resistors (secondary)).

5. Determination of reason for excessive downtime, i.e., awaiting parts not locally available, repair beyond ship or station capabilities, unfavorable weather or sea (working) conditions, etc.

6. Segregating operational failures, preventive maintenance (POMSEE) replacements, unscheduled maintenance replacements, stock defective items, and repairs made to replaceable units or plug-in assemblies.

A sound analysis system was planned in a manner which will point out those parts which are failing or being replaced at a much higher rate than others within its particular group. Since it is not feasible to compre the failure rate of a beam power klystron with that of a low voltage rectifier, categorization of parts into homogeneous groups was accomplished.

Prior to conducting an engineering analysis, various operational parameters will be investigated. Problems resulting from an individual equipment, ship or even equipments installed in the same class of ships may well be the result of improper installation, poor maintenance practices, etc., and therefore, in these cases, engineering analysis associated with circuitry should be avoided. The possibility of concurrent random replacements on a fleet-wide basis cannot be overlooked. Replacement cost, amount of actual down-time, and maintenance time resulting from the failure or replacement will likewise be considered.

Only after all these conditions have been investigated will a decision be made as to whether or not to conduct an engineering analysis. The engineering analysis encompasses factors such as investigations of circuit design and application, replacement characteristics, associated replacement, all reported trouble information (e.g., cause and type of failure), physical and environmental factors, recent equipment modification, etc.

The development and implementation of a program incorporating suitable reporting forms, systematic data preparation techniques, sophisticated data processing programs, and sound engineering analysis criteria is of little value without feedback of information to interested agencies. This program has been developed so that pertinent information will be distributed to the Bureau of Ships, major equipment contractors, and other agencies, as well as to the technician originating the reports. Specific schedules have been established for each periodic report.

A report has been designed specifically for distribution to contractors at the direction of the Bureau of Ships. The report will provide a complete time-frame history of the contractor's equipment. The following figures of merit will be provided, based on failures during operation: the mean-time-between-failures, the average repair time per failure.

The contractor will also be provided with individual summations by Equipment Model Designation in operating condition and ship or station code for the following:

1. Total failures (total number of "Operational Failure" Reports.)

2. Total operating time.

3. Total repair time.

The association between failure or replacement of parts and part provisioning is obvious. Since there is a definite need for guidance when provisioning for new equipments and establishing reprovisioning policies for old equipments, the application of fleet failure or replacement data toward this goal seemed desirable. Failure rates listed by Federal Stock Number and based on realistic population and operating time figures should provide firm guidelines for establishing spare part requirements. The combination of failure rates and average equipment operating time form a basis for reprovisioning.

The effectiveness of an established spare parts provisioning list for new equipments can be determined if data is fed back rapidly. Steps can be taken to provide additional spares for parts failing at a higher rate than predicted. Resupply rates for new parts of a new equipment can also be based on failure data.

Plans have been developed to provide BUSHIPS and the Electronics Supply Office with the following information:

1. Failure rates by Federal Stock Number.

2. Average monthly hours of operation of equipment models.

3. Replacements of Federal Stock Numbers in new equipments.

4. Failure/Replacement information on major units and electronic assemblies of modular construction.

5. Maintenance information for major units and electronic assemblies of modular construction.

The majority of this information is directly related to the Federal Stock Number since the supply system uses this form of nomenclature. To provide the information just mentioned, it was necessary to develop specific data processing programs and procedures which orientate and present failure/replacement data in a format suitable for part provisioning and reprovisioning application.

2.6.2 Maintenance Data Collection System: The Maintenance Data Collection (MDC) System is designed to provide all levels of management in the Navy Department with essential data that can be summarized by means of data processing equipment into useful management reports. At the present time, the Navy does not have a method for collecting maintenance information in a usable format. Through the use of coded entries, on standard forms, all equipment maintenance performed in the Navy will be collected.

All maintenance performed will be recorded on the prescribed forms - OPNAV Form 4700-2 and 4700-2A - by the person performing the maintenance. The codes to be used will be listed in the pertinent Equipment Identification Code (EIC) Manual. There are four separate manuals; Operations, Weapons, Engineering, and Hull and Miscellaneous. The blocks on the forms are identified by numbers and letters. The coded entries will be punched into the data cards.

The following is a recommended method of incorporating MDC within the ship's organization. An officer, preferably in the engineering department, should be designated the Maintenance Data Collection Officer as a collateral duty. He, in turn, should have a petty officer assistant whose primary duty will be MDC Petty Officer. An office such as the Engineering Log Room should be designated the MDC center for collection, review, mailing, distribution, and filing of the MDC forms and reports. The leading petty officer of each rate or space will be the Maintenance Group Supervisor. He will review each document submitted by his subordinates. He is responsible for ensuring that all MDC forms are complete and accurate. Incomplete or inaccurate maintenance data will result in erroneous manning, equipment budgeting, or work requirements action at higher levels of command.

The following data is entered on the standard form:

(a) Ship's name and hull number.

(b) Equipment identification code from EIC Manual for part repaired.

(c) Classification of the group that performed the maintenance by code number from EIC Manual.

(d) Type of maintenance action, (failure mode, frequency of routine maintenance, alteration or manufacture of new item).

(e) Manhours expended.

(f) Date action taken

(g) Serial number of equipment.

(h) Written description of malfunction or reason for maintenance action.

(i) Written description of corrective or maintenance action.

(j) List of spare parts used (CID, APL, or AN Numbers).

2.5.3 <u>Operations Reporting System:</u> The OR information such as obtained in FBM programs indicates the types and distributions of problems being experienced, the corrective action, the process by which it is applied and the effectiveness of the corrections.

3 PROBLEMS WITH EXPERIENCE DATA

Some of the reasons traditionally given for the limited use of field and operational data are:

1. Problems in Data Retrieval (what data, can't find it, too cumbersome, takes too long, costs too much, etc.).

2. Problems with Data Accuracy (can't believe what its saying, technicans do not record properly, most failures result from outside of its control and therefore should not get blamed, it never really tells me why it failed, etc.).

3. Problem in Understanding (how to use it, what does it mean, how does one relate the problem on hand, etc.).

3.1 TRADITIONAL CONCEPTS

Possibly the most common and certainly the most destructive concept concerning the retrieval of experience data is that it can be retireved in the exact orientation and form required by the "user". The probability that this can be done is at least as low as that of obtaining computer solutions to problems in response to interrogations expressed directly in the form of applied engineering equation. The analogy is highly appropriate. One cannot retrieve information from the computer without first converting the engineering language to computer language, and then programmming it in a manner dictated by both the type of information stored and the computation capability of the computer. The same is true for the stored experience data. The researcher must understand the type of data stored and how to retrieve it.

All too frequently the reliability engineer has rejected much of the current existing source of knowledge in his search for data which explicitly displays the parameters of his favorite equation, $R = e^{-t/MTBF}$. Thus, he believes that he must find a single data format which directly produces values for MTBF. The impact of this can be estimated by noting that the regularity with which he insists that clocks be designed into hundreds of components labeled "Critical". At the same time it has led him to reject much of the existing experience data as practically worthless. Until he has been helped to understand that it is not necessary for time to be recorded and explicitly displayed against each event, he will make little progress in recognizing what information is of potential value to him. As soon as he completely understand that essentially all significant events in the "real" world are performed in time oriented sequences, his horizons will be enormously expanded. It is then that he realizes that almost any component can be related to the time/sequences in which it was operated. For instance, we have two hydraulic systems in which there are two pumps each (four identical pumps). Any one pump can handle both hydraulic systems, if necessary. However, generally one pump on each system is utilized with the other pump as a back up. The pumps are alternated daily to accumulate approximately the same number of operating hours. A cruise lasts 60 days. Therefore the total hours accumulated on this type of pump is 2880 hours on a 60 day cruise per vessel.

3.2 MARSHALLING YOUR DATA SOURCES

The first element to attack, and possibly most important, is the source existing within one's own "house". This basic step is possibly the most difficult single element of the entire task. The marshalling task is unglamorous and down right tedious. The task also requires that a survey be made of how people are conducting their business and how many "road blocks" are erected in the process. Another problem which traditionally gets in the way of a successful study is the researcher's desire to describe the sources either as he wants them to be or as his management would like them to be. Describing them as they actually operate requires considerable objectivity and tact.

Each data source must be studied in detail with respect to data content, flow, storage and retrieval. After all sources have been carefully examined, it can be seen that extensive and detailed study must be made of both the source and reduced data to realize the importance of implied cross reference.

3.3 EXPERIENCE DATA INTEGRATION

Once the survey has been completed and the sources analyzed, a second phase must be undertaken, that of developing the techniques to exploit the information.

Figure 9.8 points out that experience data is only one of the four major ingredients necessary to determine the life characteristics (λt_a) of an equipment item. Another necessary portion is the "ENGINEERING INFORMATION" block while the third is the accurate integration by the interpreter(s) operating on the fourth ingredient, the appropiate process (the equation).

3.3.1 "Engineering Information": As with the use of a computer in the solution of any engineering problem, the foundation of success is built by correctly identifying and stating the problem indicated by $M_{S/f}$, the selected failure mode(s) defined appropriate to the problem. In the attempts at the solutions to the reliability aspects of the design problems, this step is the most consistently neglected and/or troublesome. The parameters are the success/failure criteria and the analogous experience data deemed appropriate to the problem. The Operations Problem Reports may assist in the selection by indicating failure mode and effect documented for the analogous item.

In addition the retriever must have the basic knowledge and understanding of the functions of the item as related to input/output requirements, sequence of operation, checkout and procedures of the system which uses this item, etc. "Exposure to failures" are generally reported at the overall-system or major system level. Item "exposure to failures" and environmental stress level must therefore be estimated by the item time/sequence functioning as applied to the system.

3.3.2 Equation to Relate Elements: The next step is to form the appropriate equation(s) which correctly relates the parameters of the problem to the degress of detail and in the form appropriate to the existing data.

The process by which the various parameters can be arithmetically combined is given by the equation on Figure 9-31.

The numerator of the equation represents the estimated item failures in the given calendar time period, t_a, for the selected failure mode(s) during the selected application activities.

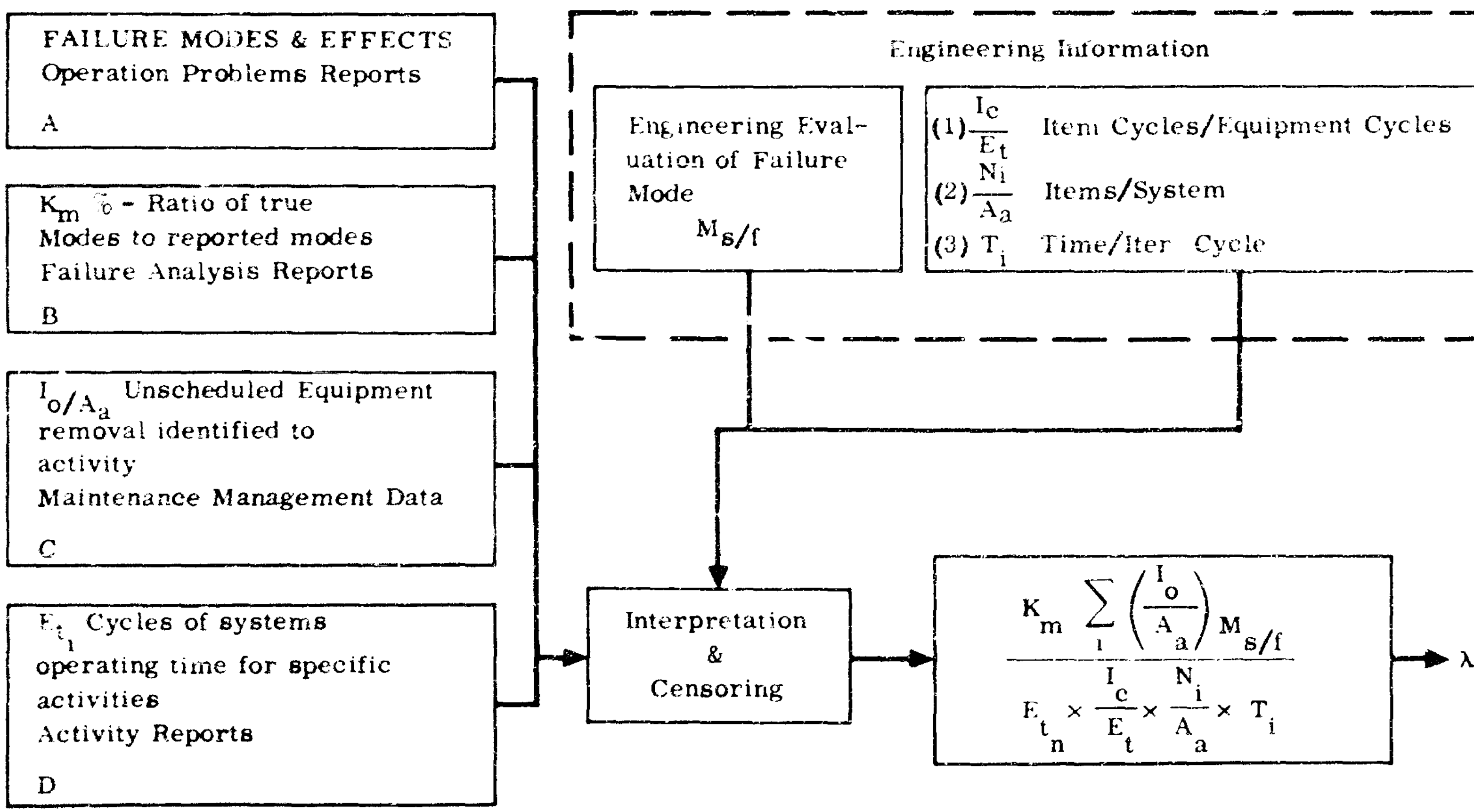
$$\sum \left(\frac{I_o}{A_a}\right) M_{S/f}$$

is the total reported numbers of unschedule removals for the selected mode(s). However, the reported failure mode(s) is not always the true failure mode(s). K_m is the estimated ratio (%) of the true mode(s) to the reported mode(s) determined from the Failure Analysis Reports.

The denominator of the equation represents the estimated "exposure to failure" from the selected application activities during the given calendar period, t_a. Activities are generally reported at the system level. From the system level, the item "exposure to failure" may be estimated by:

$$E_{t_a} \times \frac{I_c}{E_t} \times \frac{N_i}{A_a} \times T_i$$

EXPERIENCE DATA APPLICATION



Et_s is the number(s) of system cycles in the given calendar time period, t_s, for the selected application activity.

$\frac{I_c}{E_t}$ is the number(s) of item cycles per system cycle.

$\frac{N_I}{A_a}$ is the number(s) of item identified with the system.

T_i is the functioning time per item cycle.

$$E_{t_s} \times \frac{I_c}{E_t} \times \frac{N_I}{A_a} = \text{Total item cycles during } t_s.$$

$$E_{t_s} \times \frac{I_c}{E_t} \times \frac{N_I}{A_a} \times T_i = \text{Total item operating time during } t_s.$$

3.3.3 Integration of the Data: As implied in Figure 9-31, the interpreter is the primary integrator of the data. The first step is the job of "programming". Programming (forming the data retrieval requests) for experience data generally encompass several separate sources of data as well as the careful matching of details and format of the data stored by the various functions. Here we must be aware that virtually no one could collect and store data oriented to the almost infinite variety of problems which are asked of the data source.

Once the retrieval "program" is correctly formed and the data becomes available, it must be processed (sorted, ordered, combined, etc.) for application to the equation(s) employed in forming the value(s) for the chosen paramter(s).

Much information duplication will be noted on a component problem report(s); i.e., discrepancy, when discovered, part number, etc., will be indicated by "code" and/or written description. In addition, the same problem may be reported by many sources. When the duplications and redundant reports are utilized with the problem occurrance matching the activity chart, the net result of the data will be highly accurate.

"Failure rate" or the reliability estimate is determined from the ratio of the problem curve to the activity curve. In general, problems are well documented, collected, sorted, and relatively easy to locate and retrieve; however, the activities (exposure to failure, or successes), although well documented, are not generally collected and therefore making the locating and retrieval much more difficult.

Crude as this method may appear, its application has been extremely helpful in clearing up the usual difficulties encountered in even good data collection systems.

4. ESTIMATING PARAMETERS FROM THE DATA

Assuming the data sources provide a set of operating time and failure data, properly evaluated to screen out errors and data not pertinent to the problem the first step is the assumption of the underlying distribution. This assumption must be based on physical characteristics of the problem. The clues provided in the section on failure density functions will be helpful in most cases.

If the exponential distribution has been assumed, the next question is "How well does the data support the assumption?" The technique for evaluating the fit is termed the "goodness-of-fit test".

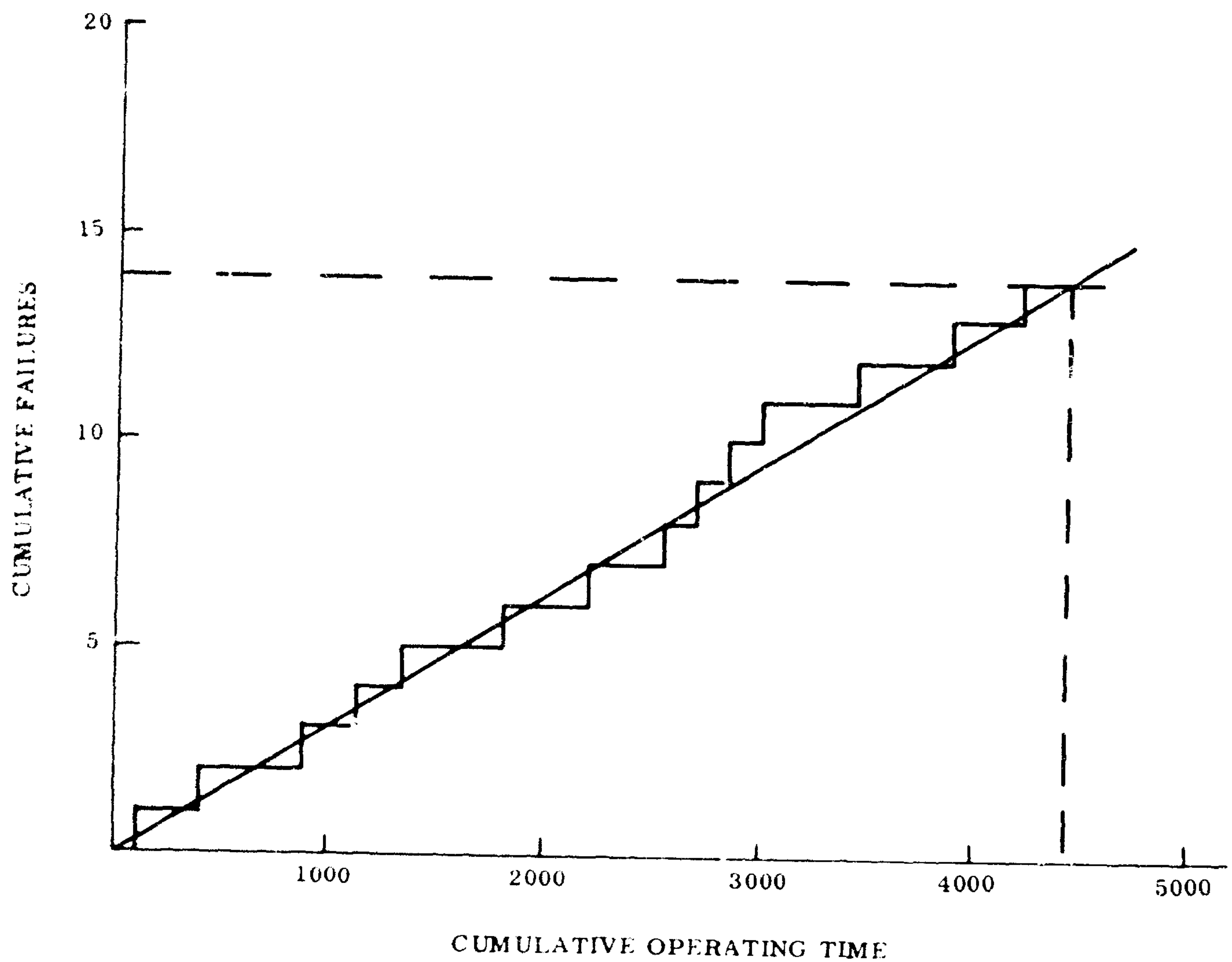
4.1 GRAPHICAL SOLUTION

A graphical procedure is useful for the quick indication of the validity of the exponential assumption provided that the number of observed failures is relatively large. One procedure is to plot the cumulative test or operating time against the cumulative number of failures as in Figure 9-34. If as shown in the example, the failures occur uniformly with time, the assumption of the exponential distribution appears valid.

4.2 CHI SQUARE GOODNESS OF FIT TEST

A more sensitive test to verify the assumption of the failure distribution can be performed analytically. From the assumed distribution function, predict the number of failures that will fall in each of several arbitrarily selected increments of time. For each such increment the predicted or expected number of failures will be np where n is the number of equipments operating and p is the probability of failure during the time in question. If k increments are selected, compute the k values of e_i the expected number of failures in the ith increment. For each increment, count the observed number of failure, o_i. The summation

DISTRIBUTION GRAPHICAL EVALUATION



$$\sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i} \quad \text{is chi-square}$$

distributed for reasonably large values of the e_i ($e_i > 5$). The number of degrees of freedom for the χ^2 distribution is k - 1, except where the sample is used to establish the expected value of MTBF. In this case the number of degrees of freedom is k - 2, one degree in effect being used in the selection of the MTBF.

Example: Test data reports on an electronic system give the following times to failure:

t_i, hours

27.0	39.0	61.4	69.6	86.3
96.5	98.2	101.5	119.2	128.6
144.0	164.6	180.0	180.0	183.8
198.2	206.8	229.1	259.5	272.6
286.4	312.1	319.3	339.0	415.9
419.5	609.8	729.1	898.7	1159.0

To test the sample against an MTBF of 300 hours, increments of time will be selected so as to have an expected value of six failures in each of five time increments. Selecting a uniform probability of 20% for each increment and the equation

$$R = e^{-\frac{t}{\theta}}, \text{ solving for t.}$$

R	t	e	o	$\frac{(e - o)^2}{e}$
.80	67	6	3	1.50
.60	150.3	6	8	.67
.40	275.2	6	9	1.50
.20	483.0	6	6	0
.00	∞	6	4	.67
				$\sum_i = 4.33$

The probability from a χ^2 table using four degrees of freedom gives a value of about 65%. This means that samples drawn from the assumed population will give you values in excess of this number (4.33) about one third of the time. This represents a reasonably good fit.

Using the data collected the total operating time is 8335 hours for 30 failures. The mean time between failures

$$\hat{\theta} = \frac{8335}{30} = 278$$

testing the sample against an assumption of 278 hours MTBF.

R	t	e	o	$\frac{(e - o)^2}{e}$
.80	62.1	6	3	1.50
.60	142.0	6	7	.17
.40	255.0	6	8	.67
.20	448.0	6	8	.67
.00	∞	6	4	.67
				3.67

From an χ^2 table using (k - 2) or three degrees of freedom the probability if found to be 70%. This is a slight improvement indicating the lower MTBF should be preferred.

4.3 TESTING DATA AGAINST OTHER DISTRIBUTIONS

The χ^2 test is applicable for testing the data against any distribution, using the parameters to be tested in the same way as was done in testing the exponential. Details can be found in Chapter 10 or in any good text on statistics.

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Chapter 10

STATISTICAL TECHNIQUES

Chapter 10

STATISTICAL TECHNIQUES

1. SEQUENTIAL ANALYSIS

Sequential Analysis is a procedure that leads to a statistical inference and in which the number of observations to be made is not determined before the experiment is begun. The procedure indicates when sufficient observations have been taken in order that a decision to accept or reject a given hypothesis can be made with predetermined producer's and consumer's risks, denoted respectively by α and β. On the average, fewer observations will be required by this procedure and its use will not increase the value of α and β.

1.1 PROCEDURE OF TESTING A HYPOTHESIS

Observations are taken one at a time. After every observation, a decision is made to accept the hypothesis, to reject the hypothesis, or continue taking observations. In order to determine which of these decisions to make, the critical region for each sample size must be determined. To do this, P_{om}, the probability that m observations collected in the successive sampling, would occur if the hypothesis H_o were true, and P_{1m}, the probability that these observations would occur if the alternative hypothesis H_1 were in fact true. To compute P_{om} the assumption is made that the hypothesis H_o is actually true. In a similar manner, to compute P_{1m}, the hypothesis H_1 is assumed to be true. When P_{om} is much larger than P_{1m}, H_o is to be accepted. When P_{1m} is much larger than P_{om}, H_1 is to be accepted. If P_{om} is approximately equal to P_{1m}, sampling will continue. A simple mathematical relationship that will express these conditions is the ratio of P_{1m} to P_{om}. The following inequalities were proven by Wald (1) to characterize the sequential test.

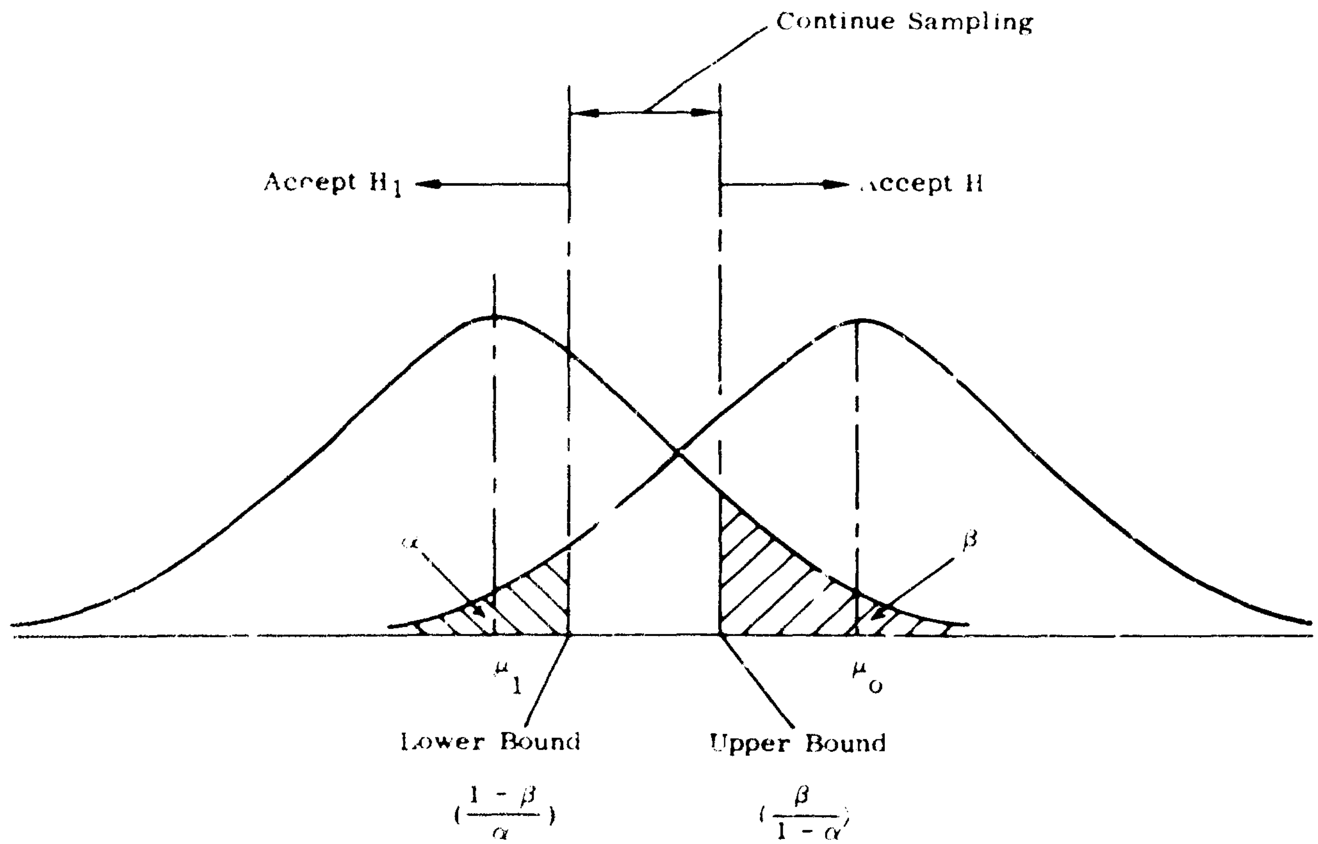
$$\text{If, } \frac{P_{1m}}{P_{om}} \geq \frac{1-\beta}{\alpha}, \text{ accept } H_1$$

$$\text{If, } \frac{P_{1m}}{P_{om}} \leq \frac{\beta}{1-\alpha}, \text{ accept } H_o$$

$$\text{If, } \frac{\beta}{1-\alpha} < \frac{P_{1m}}{P_{om}} < \frac{1-\beta}{\alpha}, \text{ continue sampling.}$$

The above inequalities are illustrated in Figure 10-3.

INEQUALITIES IN HYPOTHESIS TESTING



Sequential analysis is not restricted to any one type of probability distribution, but can be applied in general. The arithmetic necessary to deriving the equations for the bounds of the decision interval will be demonstrated below using the Binomial Probability distribution.

For this case H_o is $P = P_o$; H_1 is $P = P_1$.

$$P_{om} = P_o^{\,d}(1 - P_o)^g$$

d = defective

g = good

and,
$$P_{1m} = P_1^{\,d}(1 - P_1)^g$$

then,
$$\frac{P_{1m}}{P_{om}} = \frac{P_1^{\,d}(1 - P_1)^g}{P_o^{\,d}(1 - P_o)^g} = \left(\frac{P_1}{P_o}\right)^d \left(\frac{1 - P_1}{1 - P_o}\right)^g$$

Take natural logarithms and get,

$$\mathrm{Ln}\left(\frac{P_{1m}}{P_{om}}\right) = d\ \mathrm{Ln}\left(\frac{P_1}{P_o}\right) + g\ \mathrm{Ln}\left(\frac{1 - P_1}{1 - P_o}\right)$$

Using the above equality for $\mathrm{Ln}(P_{1m}/P_{om})$ and appropriately converted forms of the two basic inequalities for the sequential test, the following decision criteria may be derived:

1. $$\mathrm{Ln}\left(\frac{\beta}{1 - \alpha}\right) \geq d\ \mathrm{Ln}\left(\frac{P_1}{P_o}\right) + g\ \mathrm{Ln}\left(\frac{1 - P_1}{1 - P_o}\right)$$

Decision: Accept H_o

2. $\text{Ln}\left(\frac{1-\beta}{\alpha}\right) \leq d\ \text{Ln}\left(\frac{P_1}{P_o}\right) + g\ \text{Ln}\left(\frac{1-P_1}{1-P_o}\right)$

Decision: Reject H_o, i.e., accept H_1.

3. $\text{Ln}\left(\frac{\beta}{1-\alpha}\right) < d\ \text{Ln}\left(\frac{P_1}{P_o}\right) + g\ \text{Ln}\left(\frac{1-P}{1-P_o}\right) < \text{Ln}\left(\frac{1-\beta}{\alpha}\right)$

Decision: Continue sampling.

The above decision criteria can be expressed in a slightly different manner if we note that values of β, α, P_1, and P_o are to be stated before the test procedure is defined.

Let $\text{Ln}\left(\frac{\beta}{1-\alpha}\right) = K_1$, $\text{Ln}\left(\frac{1-\beta}{\alpha}\right) = K_2$,

$\text{Ln}\left(\frac{P_1}{P_o}\right) = D_1$, $\text{Ln}\left(\frac{1-P_1}{1-P_o}\right) = C_2$, and $g = m - d$.

One can restate the decision criteria as follows:

1. $K_1 - C_2 m \geq d\ (C_1 - C_2)$ Accept H_o

2. $K_2 - C_2 m \leq d\ (C_1 - C_2)$ Reject H_o

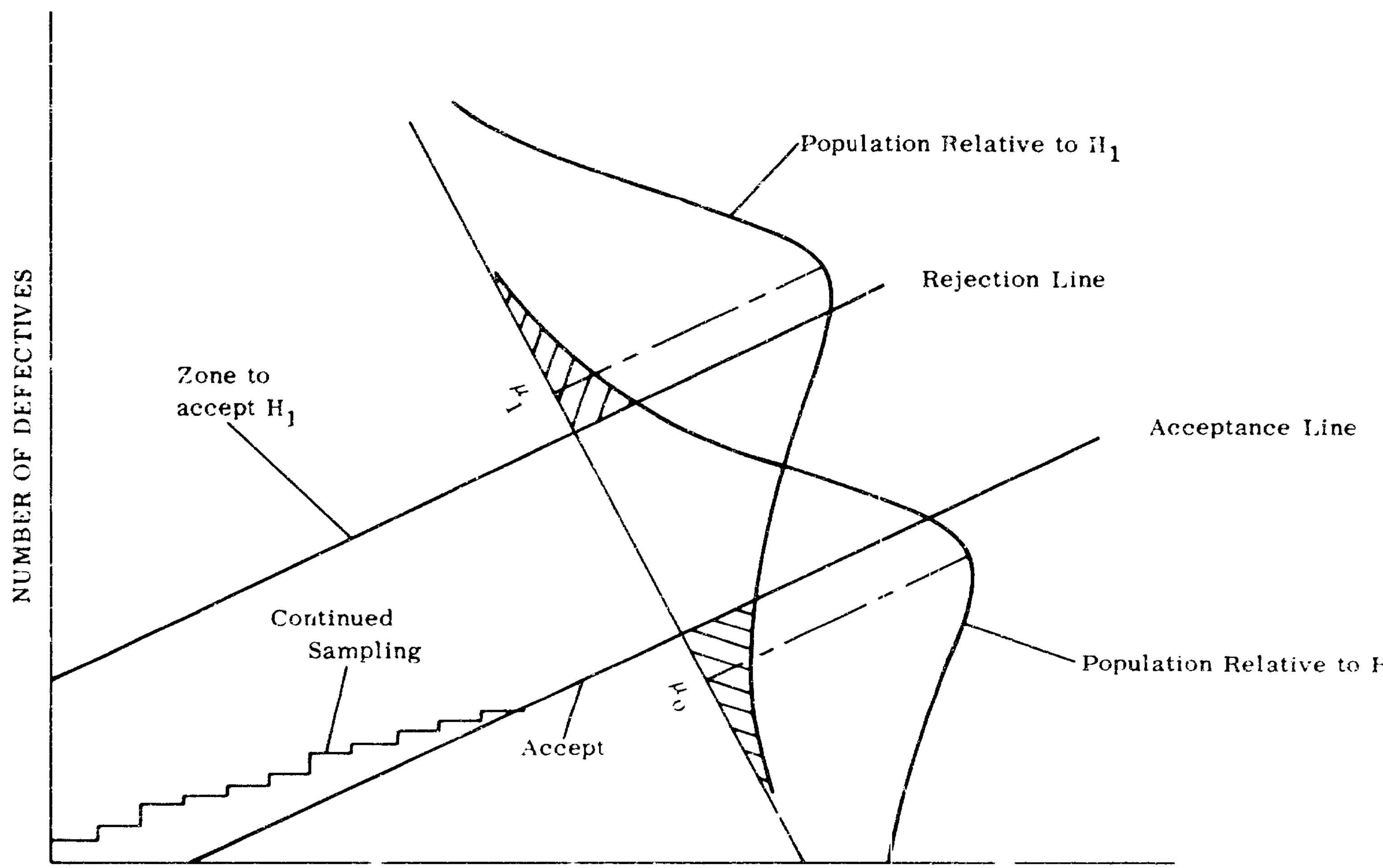
3. $K_1 - C_2 m < d\ (C_1 - C_2) < K_2 - C_2 M$ Continue Sampling

The decision boundary line functions,

$$\frac{K_1}{C_1 - C_2} - \frac{C_2}{C_1 - C_2} m \quad \text{and} \quad \frac{K_2}{C_1 - C_2} - \frac{C_2}{C_1 - C_2} m ,$$

are graphically presented in Figure 10-6.

ACCEPTANCE SITUATION



To illustrate the method of sequential testing, consider a test of the honesty of a coin that is suspected of giving too many heads. A Binomial Sequential test will be made of the hypothesis H_o: $P_o = 0.5$ against an alternate hypothesis H_1: $P_1 = 0.7$. Let the type I and type II errors be $\alpha = .10$ and $\beta = 0.20$.

1. $$K_1 = \text{Ln}\left(\frac{\beta}{1-\alpha}\right) = \text{Ln}\left(\frac{.2}{.9}\right) = -1.504$$

2. $$K_2 = \text{Ln}\left(\frac{1-\beta}{\alpha}\right) = \text{Ln}\left(\frac{.8}{.1}\right) = 2.079$$

3. $$C_1 = \text{Ln}\left(\frac{P_1}{P_o}\right) = \text{Ln}\left(\frac{7}{5}\right) = 0.337$$

4. $$C_2 = \text{Ln}\left(\frac{1-P_1}{1-P_o}\right) = \text{Ln}\left(\frac{3}{5}\right) = -0.511$$

5. $$C_1 - C_2 = 0.337 - (-0.511) = 0.848$$

6. $$\frac{K_1}{C_1 - C_2} - \frac{C_2}{C_1 - C_2}\, m = -1.8 + .6m \qquad \text{(lower boundary)}$$

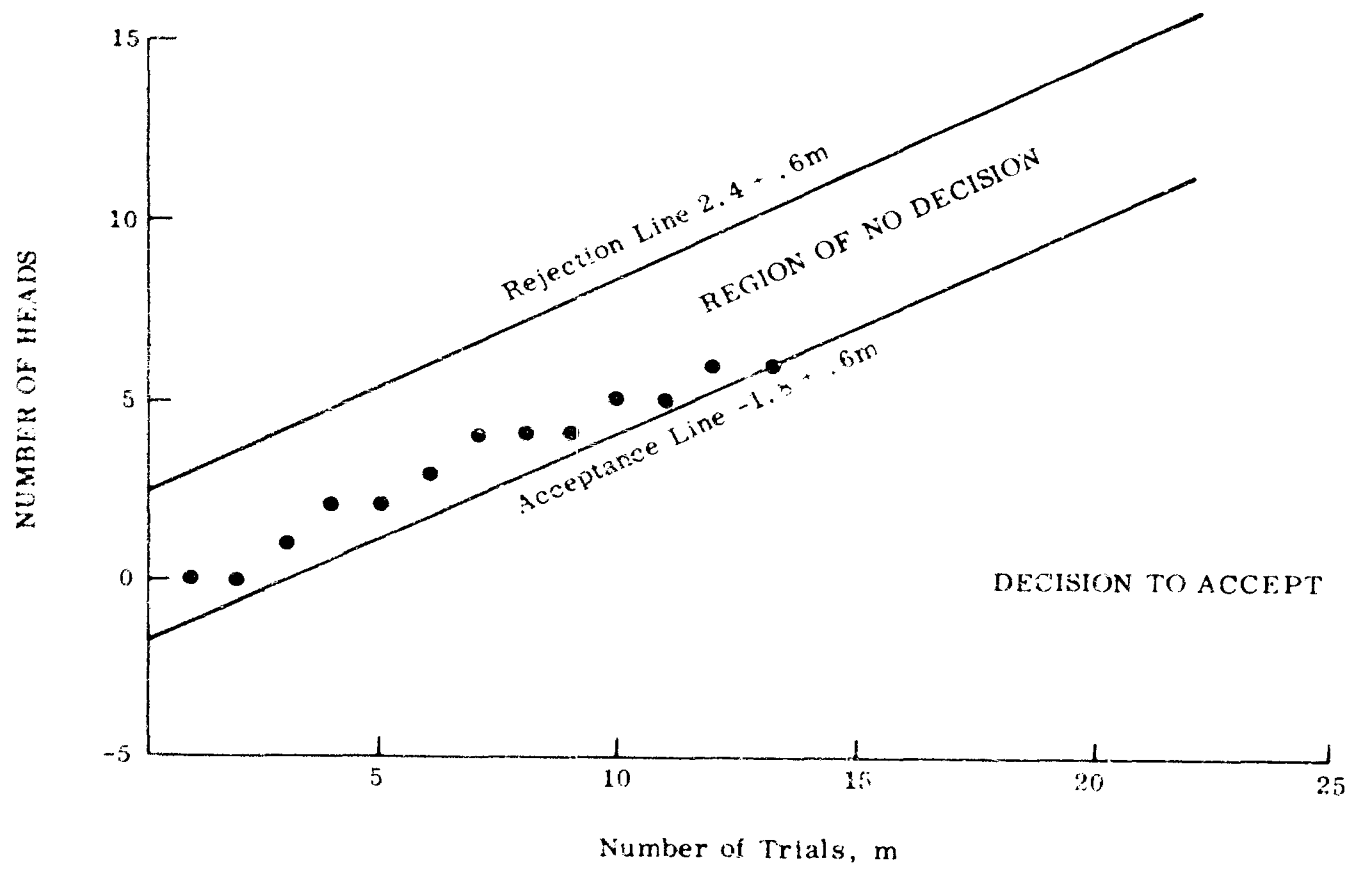
7. $$\frac{K_2}{C_1 - C_2} - \frac{C_2}{C_1 - C_2}\, m = 2.4 + .6m \qquad \text{(upper boundary)}$$

The lower boundary line separates the acceptance region from the no-decision region; it is, therefore, called the acceptance line. The upper boundary line separates the rejection region from the region of no-decision; it is, therefore, called the rejection line.

At each toss of the coin, a decision must be made as to the honesty of the coin. The results of tossing a coin are given in Figure 10-8. From this illustration, it is noted that the test was finished after 13 trials since a decision was made at that time. The hypothesis that P = 0.5 was accepted over the alternative P_1. If the alternative had been $P_1 = 0.65$ a larger number of trials would have been required, on the average, to arrive at a decision with the same probabilities for the risks.

The result of a sequential significance test analysis is a

TEST OF PROBABILITY, HEAD



pair of lines that will divide the sample space into three regions such that after each test a decision can be made to either continue testing or to accept one or the other of two hypotheses. It is then a simple process to represent the results of each test as a score and to terminate the test as soon as the cumulative total of the score has reached either of two limits. In the simpler cases the two lines will be straight lines as was the case with the coin. It will then be necessary only to plot some function of the observations on a chart where the two straight lines indicate the limits of interest. If these lines are parallel, they will have the same slope. The information needed to plot them will be the slope and their intercepts. The information is given below for each distribution function discussed. The test is then to be terminated when one of the lines is reached. In practice, however, the line will generally be crossed; so the errors involved will actually be less than that which is specified.

It is now desired to outline a sequential testing procedure for several well-known distribution functions. The following definitions are necessary:

General Terms:

α = Producer's or Vendor's risk - Probability of rejecting the reliability of the system even though the reliability is satisfactory. - (The probability of a type I error).

β = Consumer's risk - Probability of accepting the reliability of the system, when the actual reliability is not as good as the specification. - (The probability of a type II error).

n = Sample Size - number of observations.

$\bar{n}$ = The Average sample number - the expected number of tests that must be made before a decision will be reached.

m = Number of items tested.

h_0 = The intercept of the line forming the lower boundary line of decision.

h_1 = The intercept of the line forming the upper boundary line of decision.

s = The common slope of the two lines forming the boundaries of the regions of decision.

Normal Test or "t" test:

μ = Mean of normal distribution.

σ = Standard deviation of a normal distribution.

$\frac{\sigma}{\sqrt{n}}$ = The standard deviation of the arithmetic mean of the observations.

$\bar{x}$ = Mean of the observations of x.

Exponential test:

θ = Mean Time to Failure.

$\hat{\theta}$ = Estimate of the Mean Time to Failure.

e = Acceptance Number - A value of time to failure which if exceeded by the sample mean time to failure will assure the required reliability coefficient.

r = Number of Failures.

Poisson test:

m_0, m_1 = Parameter of the Poisson distribution.

In the general statistical testing situation the error made when a correct null hypothesis is rejected (e.g., rejecting an item meeting the specification), is called a type I error and the probability of a type I error is called the significance level -- usually denoted by the symbol α. The error made when a true alternative hypothesis is rejected, (e.g., acceptance of a defective item), is called a type II error. The probability of not making a type II error is called the power. Thus, Power equals one (1) minus the Consumer's risk.

1.2 NORMAL DISTRIBUTION

The first distribution to be considered is the normal distribution. A test of the hypothesis $H_0: \mu = \mu_0$ against an alternative $H_1: \mu = \mu_1$ is developed for measurements from a normal population. It is important to detect the difference between the two means. The type I error α, is the risk of asserting a difference when none exists, and β, the type II error, is the risk of asserting no difference when the mean is really different.

To construct the chart, convenient values are chosen for the two scales. On the horizontal axis is the number of tests or observations, and on the vertical axis is the function measured.

The sequential testing procedure for normal distribution (with σ known) is described in the following manner.

1. Calculate:

Slope of boundary lines:

$$S = \frac{\mu_o + \mu_1}{2}$$

Intercepts of boundary lines:

$$h_o = B\frac{\sigma^2}{\delta}, \quad h_1 = A\frac{\sigma^2}{\delta} \quad \text{where,}$$

$$\delta = \mu_1 - \mu_o, \quad A = \text{Ln}\frac{1-\beta}{\alpha}, \quad B = \text{Ln}\frac{\beta}{1-\alpha}$$

Average sample number required:

$$\bar{n}_o = \frac{(1-\alpha)\,h_o + h_1}{\mu_o - S} \qquad \text{if } \mu = \mu_o$$

$$\bar{n}_1 = \frac{h_o + (1-\beta)h_1}{\mu_1 - S} \qquad \text{if } \mu = \mu_1$$

$$\bar{n}_s = \frac{-h_o h_1}{\sigma^2} \qquad \text{if } \mu = \frac{\mu_o + \mu_1}{2}$$

2. Plot the boundary lines:

$$T_o = h_o + ns$$

$$T_1 = h_1 + ns$$

3. Proceed with testing. A decision is reached when a boundary is crossed.

1.3 BINOMIAL DISTRIBUTION

The plan for sequential testing for the binomial distribution has already been discussed.

The sequential testing procedure for binomial distribution is computed in the following manner.

1. Calculate:

Slope of boundary lines

$$S = \frac{\ln \frac{q_o}{q_1}}{\ln \frac{P_1}{P_o} + \ln \frac{q_o}{q_1}}, \quad \text{where } q = 1 - p$$

Intercepts of boundary lines

$$h_o = \frac{K_1}{\ln \frac{P_1}{P_o} + \ln \frac{q_o}{q_1}} \qquad \text{where } K_1 = \ln \frac{\beta}{1 - \alpha}$$

$$h_1 = \frac{K_2}{\ln \frac{P_1}{P_o} + \ln \frac{q_o}{q_1}} \qquad K_2 = \ln \frac{1 - \beta}{\alpha}$$

Average sample numbers required

$$\bar{n}_o = \frac{(1 - \alpha)h_o + h_1}{P_o - S} \qquad \text{if } P = P_o$$

$$\bar{n}_s = \frac{h_o + (1 - \beta)h_1}{P_1 - S} \qquad \text{if } P = P_1$$

$$\bar{n}_s = \frac{-h_o h_1}{S(1 - S)} \qquad \text{if } p = S$$

2. Plot the boundary lines:

$$d_m = h_o + mS$$

$$d_m = h_1 + mS$$

3. Proceed with testing. A decision is reached when a boundary is crossed.

1.4 CHI-SQUARE DISTRIBUTION

When the mean-time-to-failure must be estimated, the Chi-Square distribution is employed. It has the following properties:

The frequency curves extend from zero to infinity.

In the case n = 1, the curve is merely the positive half of the normal curve; as n tends to infinity, the distribution tends to normality, but rather slowly.

When n is greater than 1 the function is zero at the origin, rises to a mode at n - 2 and then falls off again to infinity.

The moments about the mean are:

$$m_2 = 2n$$

$$m_3 = 8n$$

$$m_4 = 48n + 12n^2$$

The distribution function is an incomplete gamma function.

The sequential testing procedure for Chi-square distribution is computed in the following manner.

1. Calculate:

   Values of $\chi^2/2r$ for upper and lower boundary lines, using values of T_1, T_2, α, and β selected from previous data.

2. Plot the boundary lines

$$\text{Upper:} \quad \hat{T} = T_2 \frac{\chi^2_{(1-\beta)}}{2r}$$

$$\text{Lower:} \quad \hat{T} = T_1 \frac{\chi^2_{\alpha}}{2r}$$

3. Proceed with testing. A decision is reached when a boundary is crossed.

1.5 POISSON DISTRIBUTION

When an event has only a very small, constant probability of occurring, but many trials are made so that the event does in fact happen with measurable frequency, the number of occurrences is given by the Poisson distribution. While the probability of a given component failure at any time is very small, where many components are used in a given system, failures are distributed at random, this frequency will be described by the Poisson distribution.

Problems where the Poisson distribution applies are met in connection with counting, for example, in determining the number of neutron particles reaching a counter in a given time interval.

The sequential testing procedure for Poisson distribution is calculated in the following manner.

1. Calculate:

Slope of boundary lines

$$s = \frac{m_2 - m_1}{\log \frac{m_2}{m_1}}$$

Intercepts of boundary lines

$$h_1 = \frac{\mathrm{Ln}\left(\frac{1-\beta}{\alpha}\right)}{\mathrm{Ln}\ \frac{m_2}{m_1}}$$

$$h_o = \frac{\mathrm{Ln}\left(\frac{-}{1 - }\right)}{\mathrm{Ln}\, \frac{m_2}{m_1}}$$

Average sample numbers required when $m = m_1$, $m = m_2$ and $m = s$

$$\bar{n}_o = \frac{(1 - \;)h_o + \;h_1}{m_1 - s}$$

$$\bar{n}_1 = \frac{\;h_o + (1 - \;)h_1}{m_2 - s}$$

$$\bar{n}_s = \frac{-h_o h_1}{s}$$

2. Plot the boundary lines:

$$T_o = h_o + ns$$

$$T_1 = h_1 + ns$$

3. Proceed with testing. A decision is reached when a boundary is crossed.

1.6 EXPONENTIAL DISTRIBUTION

The exponential distribution has been observed for many types of complex systems and may be used for those parts and systems which are so complex that many types of deterioration with different rates are operable.

It is a special case of the Gamma distribution and is characterized by a constant failure rate. The confidence interval for the mean of an exponential distribution from a random sample of times-to-failure can be obtained by using the Chi-square distribution with 2r degrees of freedom, where r is the number of failures observed.

The sequential testing procedure for exponential distribution is calculated in the following manner.

1. Calculate:

Slope of boundary lines

$$s = \frac{Ln\left(\frac{T_1}{T_2}\right)}{\frac{1}{T_2} - \frac{1}{T_1}}$$

Intercepts of boundary lines

$$h_o = \frac{A}{\frac{1}{T_2} - \frac{1}{T_1}} \qquad \text{where,} \quad A = Ln\,\frac{\alpha}{1-\beta}$$

$$B = Ln\,\frac{1-\alpha}{\beta}$$

$$h_1 = \frac{B}{\frac{1}{T_2} - \frac{1}{T_1}}$$

Average sample numbers required when $T = T_1$, $T = T_2$, and $T = s$

$$\bar{n}_o = \frac{(1-\alpha)\,B + A}{\left(\frac{T_1}{T_2} - 1\right) + Ln\,\frac{T_2}{T_1}}$$

$$\bar{n}_1 = \frac{\beta B + (1-\beta)A}{\left(1 - \frac{T_2}{T_1}\right) + Ln\,\frac{T_2}{T_1}}$$

$$n_s = \frac{-BA}{\left[Ln\left(\frac{T_1}{T_2}\right)\right]^2}$$

2. Plot the boundary lines:

$$T_o = h_o + rs$$

$$T_1 = h_1 + rs$$

3. Proceed with testing. A decision is reached when a boundary is crossed.

Several different distributions are used to describe the parameters found in the literature of reliability. It is necessary for the engineer to have a working knowledge of these distributions in order to understand their applications, their limitations, and the time and labor that can be saved by their proper use.

When statistical tests of significance are set up, it is the responsibility of the engineer setting up the test to consult with the statistician in order to determine a sequential testing procedure that can be utilized in order to conserve time and money and reach a conclusion that will provide the greatest amount of confidence in the results.

2. TEST PROCEDURES SUMMARY

The foregoing discussion has considered many of the theoretical concepts involved in testing statistical hypothesis and some of the practical problems associated with these concepts. In the forthcoming section actual testing procedures will be summarized.

2.1 CHI SQUARE (χ^2) "GOODNESS OF FIT" TEST

This procedure is used to determine whether or not a set of observed values is consistent with a uniquely specified density function. This uniquely specified density function is the null hypothesis. The alternative hypothesis is that the true density function is other than that specified. This alternative includes both density functions of other forms and density function of the same form as that specified but with different values for the parameter.

1. All possible values that an observation can take on are divided into N classes, each class being some "conveniently" chosen interval of the form $[a_i \le x < A_{i+1}]$ with $a_{i+1} > a_i$.

2. The probability, p_i, that an observation will fall into the ith class is computed using the density function, $f_0(x)$, specified by the null hypothesis, i.e.,

$$p_i = \int_{a_i}^{a_{i+1}} f(x)\,dx$$

3. The expected number, e_i, of observations falling into the ith class (for each value of i) is computed using the equation

$$e_i = n \cdot p_i$$

where n is the number of observations. It is required that each e_i be greater than five. There may be some regrouping of classes in order to fulfill this requirement. It is now assumed that all the possible values of an observation has been divided into N classes and that the expected number in each class is greater than 5.

4. Each of the n observations, $\{x_1, x_2, \ldots\ldots, x_n\}$ is put into its proper class. The number of observations, O_i, in each class is then computed.

5. The quantity, u, is, then computed where

$$u = \sum_{i=1}^{n} \frac{(e_i - O_i)^2}{e_i}$$

6. The quantity, u, has a density function that is χ^2 with N-1 degrees of freedom. The desired significance level, α, is now used. Entering the χ^2 tables with N-1 degrees of freedom and α, a value, χ_0^2, such that

$$P(\chi^2 > \chi_0^2) = \alpha \text{ or } P(\chi^2 \le \chi_0^2) = 1 - \alpha$$

is obtained.

7. If $u \le \chi_0^2$, the data is said to be consistent with the null hypothesis at the α significance level; if $u > \chi_0^2$ the data is said to be inconsistent with the hypothesis at the α significance level, i.e., the null hypothesis is rejected.

The following point regarding the χ^2 "Goodness of Fit" test may be noted. Suppose that the density function, f(x), has k(k<N-1) parameters not specified by the null hypothesis. One could use the observations $\{x_1, \ldots, x_n\}$ to provide estimates, via the maximum likelihood estimator, of the k parameters. These estimated values, $\{\hat{\theta}_1, \hat{\theta}_2, \ldots, \hat{\theta}_k\}$, could then be substituted into the density function and expected values computed as was done previously. The statistic, u, now has a density function that is χ^2 with N-1-k degrees of freedom.

Examples:

1. A die was cast 360 times with the following result.

Result of toss	1	2	3	4	5	6
Frequency	59	65	52	63	67	54

Are the data consistent with the null hypothesis that the die is true at the 0.05 significance level.

Step 1: $H_0: p_1 = p_2 = p_3 = p_4 = p_5 = p_6 = \frac{1}{6}$

$$e = e_1 = e_2 = e_3 = e_4 = e_5 = e_6 = \frac{1}{6} \times 360 = 60.$$

Step 2: χ_0^2 (5 degrees of freedom, $\alpha = 0.05$) = 11.1

Step 3:

$$u = \frac{(60-59)^2}{60} + \frac{(60-65)^2}{60} + \frac{(60-52)^2}{60} + \frac{(60-63)^2}{60} + \frac{(60-67)^2}{60}$$

$$+ \frac{(60-54)^2}{60} = \frac{1}{60}[1 + 25 + 64 + 9 + 49 + 36] = \frac{184}{60} = 3.07$$

Step 4: $u \leq \chi_0^2$. Hypothesis is retained.

2. A Monte Carlo method is used to generate times-to-failure having a density function, $\lambda e^{-\lambda x}$ where $\lambda = \frac{1}{36}$. Two thousant such times have been generated. The class data are presented in Table 10.1. Each class interval represents 3 time units from 0-60 with the last interval containing all observations greater than 60.

Are the 2000 observed values consistent with $H_0: f(x) = \lambda e^{-\lambda x}$ where $\lambda = 1/36$ at the 0.10 significance level?

TABLE 10.1

SUMMARY OF MONTE CARLO SAMPLING

FROM DENSITY FUNCTION, $\frac{1}{36} e^{-\frac{1}{36}x}$

Class Interval Number	Class Interval Definition	Observed Number in Class, O_i	Expected Number in Class, e_i	$\frac{(e_i - O_i)^2}{e_i}$
1	$0 \le t < 3$	147	159.9	1.0407
2	$3 \le t < 6$	170	147.1	3.5650
3	$6 \le t < 9$	131	135.4	0.1430
4	$9 \le t < 12$	117	124.5	0.4518
5	$12 \le t < 15$	113	114.6	0.0223
6	$15 \le t < 18$	110	105.4	0.2008
7	$18 \le t < 21$	99	97.0	0.0412
8	$21 \le t < 24$	87	89.2	0.0543
9	$24 \le t < 27$	81	82.1	0.0147
10	$27 \le t < 30$	81	75.5	0.4007
11	$30 \le t < 33$	83	69.5	2.6223
12	$33 \le t < 36$	73	63.9	1.2959
13	$36 \le t < 35$	61	58.8	0.0823
14	$39 \le t < 42$	48	54.1	0.6878
15	$42 \le t < 45$	40	49.8	1.9285
16	$45 \le t < 48$	54	45.8	1.4681
17	$48 \le t < 51$	35	42.2	1.2284
18	$51 \le t < 54$	30	38.8	1.9959
19	$54 \le t < 57$	31	35.7	0.6188
20	$57 \le t < 60$	33	32.8	0.0012
21	$t < 60$	376	377.8	0.0086
		2000	2000	17.8723

Step 1. $H_0 \cdot \frac{1}{36} e^{-\frac{1}{36}x}$

(a) $p_1 = \int_0^3 \frac{1}{36} e^{-\frac{1}{36}x} dx = 1 - e^{-\frac{1}{12}}$

$e_1 = 2000 \; (1 - e^{-\frac{1}{12}}) = 159.9$

(b) $p_2 = \int_3^6 \frac{1}{36} e^{-\frac{1}{36}x} dx = e^{-\frac{1}{12}} - e^{-\frac{1}{6}}$

$e_2 = 2000 \; (e^{-\frac{1}{12}} - e^{-\frac{1}{6}}) = 147.1$

etc.

The values, e_i, are also presented in Table 10.1.

Step 2. χ_0^2 (20 degrees of freedom, $\alpha = 0.10$) = 28.4

Step 3. $u = \sum_{i=1}^{21} \frac{(e_i - o_i)^2}{e_i} = 17.87$

Step 4. $u < \chi_0^2$ so null hypothesis is not rejected.

3. If $H_0: f(x) = \lambda e^{-\lambda x}$ did not specify λ, then step (1) would have used the data to obtain an estimated value, $\hat{\lambda}$, for λ. The value, $\hat{\lambda}$, rather than $\lambda = 1/36$ would then be used to compute values for e_i. The only other change would then be determining χ_0^2 using the χ^2 tabular values for 19 degrees of freedom rather than 20.

Before discussing other test procedures there are a number of points illustrated by the above examples that should be explicitly stated.

In the second example, a χ_c^2 value of 28.4 (α = 0.10 and 20 degrees of freedom) was used. If the null hypothesis is true then the odds are 9:1 against obtaining a value of u greater than χ_c^2. If a set of observations produces a value, u_1, that is greater than χ_c^2 we have one of two choices. One choice is to assume that the null hypothesis is true despite the fact that an "unlikely" event (9:1 odds against it) has occurred. The second choice is to reject the null hypothesis. This second choice represents the attitude taken in the development of the concepts of testing statistical hypothesis.

The next point concerns the observed numerical value of u in the second example. One may remember that u_{obs} = 17.9. Furthermore, H_0 was not rejected since $u_{obs} < \chi_c^2 = 28.4$. Suppose u_{obs} were 28.0 rather than 17.9. Statistics makes no distinction between these two values. The rejection region, $[28.4, \infty]$, has been selected to yield a given significance level. If one decides, after calculating 28.0 as the value for u, to reject H_0, he is, in effect, changing the significance level. He is not acting in accordance with his pre-calculation stated desires. Thus, while the two values indicate different degress of consistency between theory (expected values) and practice (observed values), both degrees of consistency are within the limit specified by the stated significance level.

In a similar vein remember that, in general, acceptance or rejection of the null hypothesis is a matter of comparison of degree of consistency between theory (or theories) and practice - it is not a 100% positive statement concerning the truth of the null hypothesis or the alternative. Indeed, to be extremely literal, it does not concern the term "truth" at all; rather, it concerns degrees of consistency between a set of data and two hypotheses as well as a selection of some limiting degree of consistency to determine which of two hypotheses is to be preferred.

2.2 THE "NORMAL" TEST

Case 1. A sample of m observations is taken from a $n(x;\mu,\sigma)$ population where $\sigma = \sigma_0$ is a specified number.

Test $H_0: \mu = b$ (b a specified number) against $H_1: \mu > b$ at a significance level of α.

Step 1: Determine a_α from cumulative Normal tables such that $N(a_\alpha; 0, 1) = 1 - \alpha$.

Some typical values of a_α are:

α	$1-\alpha$	a_α	α	$1-\alpha$	a_α
0.20	0.80	0.842	0.05	0.95	1.645
0.10	0.90	1.282	0.01	0.99	2.326

Step 2: Calculate $\overline{X}$ (arithmetic average) of observations.

Step 3: Calculate $\dfrac{\overline{X} - b}{\sigma_0/\sqrt{m}} = r$

Step 4: If $r > a_\alpha$ reject H_0 in favor of H_1; otherwise H_0 is retained.

Case 2. Same as Case 1, but $H_0: \mu = b$ is to be tested against $H_1: \mu > b$ at a significance level of α.

Step 1: Same as Steps 1, 2, and 3 of Case 1.

Step 4: If $r > a_\alpha$, reject H_0 in favor of H_1, otherwise H_0 is to be retained.

[This is called a one-tailed test.]

Case 3. Same as Case 1, but $H_0: \mu = b$ is to be tested against $H_1: \mu \neq b$ at a significance level of α.

Step 1. Compute $\alpha' = 1 - \frac{\alpha}{2}$

Step 2. Determine a_α from the equation $N(a_\alpha; 0, 1) = P(y \leq a_\alpha)$ using Cumulative Normal tables.

Typical values of a_α are:

α	$1-(\frac{\alpha}{2})$	a_α	α	$1-(\frac{\alpha}{2})$	a_α
0.20	0.90	1.282	0.05	0.975	1.960
0.10	0.95	1.645	0.01	0.995	2.576

Step 3. Calculate $r = \dfrac{\overline{X} - b}{\sigma_0/\sqrt{m}}$

Step 4. If $r < -a$ or $r > a$ reject H_0 in favor of H_1; otherwise H_0 is retained.

[This is called a two-tailed test.]

Case 4. A sample of m_1 observations is taken from a $n(x;\mu_1,\sigma_1)$ population where σ_1 is a specified number.

A second sample of m_2 observations is taken from a $n(x;\mu_2,\sigma_2)$ population where σ_2 is a specified number.

$H_0:\mu_1 = \mu_2$ is to be tested against $H_1:\mu_2 > \mu_1$ at a significance level of α.

Step 1. Determine a_α such that $N(a_\alpha;\ 0,\ 1) = 1 - \alpha$ as was done in Case 1.

Step 2. Compute $r = \dfrac{\overline{X}_2 - \overline{X}_1}{\sqrt{\dfrac{\sigma_1^2}{m_1} + \dfrac{\sigma_2^2}{m_2}}}$

where $\overline{X}_1$ is the arithmetic average of the observations in the first sample and $\overline{X}_2$ is the arithmetic average of the observations in the second sample.

Step 3. If $r > a_\alpha$ reject H_0; otherwise retain H_0.

Case 5. Same as Case 4 but $H_0:\mu_1 = \mu_2$ is to be tested against $H_1:\mu_1 \neq \mu_2$ at a significance level of α.

Step 1: Compute $\alpha' = 1 - \frac{\alpha}{2}$ and a_α such that $N(a_\alpha;\ 0,\ 1) = \alpha'$ as was done in Case 3.

Step 2: Compute $r = \dfrac{\overline{X}_2 - \overline{X}_1}{\sqrt{\dfrac{\sigma_1^2}{m_1} + \dfrac{\sigma_2^2}{m_2}}}$

Step 3: If $r < -a_\alpha'$, or $r > a_\alpha'$, reject H_0; if $-a \leq r \leq a_\alpha'$ accept H_0.

It may be noted that rejection regions have been defined by inequalities of the form $r > a$ with acceptance when $r \leq a$. Changing rejection inequalities to $r \geq a$ and acceptance when $r < a$

does not require any changes in previous steps.

The following cases require a density function known as the "Student t" and the procedures are called "t tests".

In the six "Normal" tests above it was always assumed that the standard deviation values were known. When the standard deviations are unknown, estimates of σ must be obtained from the sample observations. If estimates, s, of σ are used, then the "Normal" test is not applicable and the "t" test must be used instead The "t" distribution is used in the same fashion as the "Normal" for both one sided and two sided tests.

Values of the cumulative ($F(d) = P(x \leq d)$ Student distribution are presented in Figure 10-55. It may be noted that to obtain a particular tabular entry, two numbers are required, a value for n(left most column) and a value for F(d). The entry found is, then, the appropriate value for d. (The value of n is called the number of degrees of freedom.) As an example, for 19 degrees of freedom and F(d) = 0.975, the required value for d is 2.093. We shall denote this value obtained from the table as $t_{0.975,19}$ = 2.093.

The following notation will be used in describing various "t Test" procedures.

1. $\bar{X}$ will denote the sample arithmetic average. In particular, if there are m observations

$$\bar{X} = \frac{\sum_{j=1}^{m} x_j}{m}$$

If more than one sample is involved, a subscript on $\bar{X}$ will be used to indicate the applicable sample. The jth observation in the ith sample will be denoted by x_{ij}

thus $$\bar{X}_i = \frac{\sum_{j=1}^{m_i} x_{ij}}{m_i}$$

where m_i denotes the number of observations in the ith sample.

2. T will denote the total of the observations

$$\overline{X} = \frac{T}{m} \text{ or } m\overline{X} = T$$

$$\overline{X}_i = \frac{T_i}{m_i} \text{ or } m_i\overline{X}_i = T_i$$

3. S^2 will denote the sample standard variance

$$S^2 = \frac{1}{m-1}\sum_{j=1}^{m}(X_j-\overline{X})^2 = \frac{1}{m-1}\left[\sum_{j=1}^{m}X_j^2 - \frac{T^2}{m}\right]$$

$$S_i^2 = \frac{1}{m-1}\sum_{j=1}^{m_i}(X_{ij}-\overline{X}_i)^2 = \frac{1}{m_i-1}\left[\sum_{j=1}^{m_i}X_{ij}^2 - \frac{T_i^2}{m_i}\right]$$

4. $S = \sqrt{S^2}$ (or $S_i = \sqrt{S_i^2}$) is the sample estimate of the standard deviation.

Case 6. A sample of m observations is taken from a $n(x;\mu,\sigma)$ population. $H_0: \mu = b$ is to be tested against $H_1: \mu > b$ at a significance level of α.

Step 1. Determine $t_{1-\alpha,m-1}$ using Figure 10-55.

Step 2. Calculate S and then $r = \dfrac{\overline{X} - b}{S/\sqrt{m}}$

Step 3. If $r > t_{1-\alpha,m-1}$ reject H_0; otherwise H_0 is retained.

Case 7. Same as Case 6 but $H_0: \mu = b$ is to be tested against $H_1: \mu < b$ at a significance level of α.

Step 1. Determine $t_{1-\alpha,m-1}$ as above.

Step 2. Calculate S and then $r = \dfrac{\overline{X} - b}{S/\sqrt{m}}$

Step 3. If $r < -t_{1-\alpha,m-1}$ reject H_0; otherwise H_0 is retained.

Case 8. Same as Case 6 but $H_0: \mu = b$ is to be tested against $H_1: \mu \neq b$ at an α level of significance.

Step 1. Compute $\gamma' = 1 - \alpha/2$.

Step 2. Determine $t_{\gamma', m-1}$ using Figure 10-26.

Step 3. Compute S and then $r = \dfrac{\bar{X} - b}{S/\sqrt{m}}$

Step 4. If $r < -t_{\gamma', m-1}$ or $r > t_{\gamma', m-1}$ reject H_0 in favor of H_1; otherwise H_0 is retained.

Case 9. A sample of size m_1 is taken from an $n(x;\mu_1,\sigma)$ population. A second sample of size m_2 is taken from a different $n(x;\mu_2,\sigma)$ population. It is assumed that the σ of these two populations are equal and that this common value is to be determined using sample values.

$H_0: \mu_1 = \mu_2$ is to be tested against $H_1: \mu_2 > \mu_1$ at a significant level of α.

Step 1. Determine $t_{1-\alpha, m_1 + m_2 - 2}$

Step 2. Compute $e = \dfrac{m_1 \cdot m_2}{m_1 + m_2}$

Step 3. Compute

$$S^2 = \frac{1}{m_1 + m_2 - 2}\left[\sum_{j=1}^{m_1} (X_{1j} - \bar{X}_1)^2 + \sum_{j=1}^{m_2} (X_{2j} - \bar{X}_2)^2\right]$$

$$= \frac{1}{m_1 + m_2 - 2}\left[\sum_{j=1}^{m_1} X_{1j}^2 - \frac{T_1^2}{m_1} + \sum_{j=1}^{m_2} X_{2j}^2 - \frac{T_2^2}{m_2}\right]$$

Step 4. Compute $r = \dfrac{\bar{X}_2 - \bar{X}_1}{S/\sqrt{e}}$

Step 5. If $r > t_{1-\alpha, m_1 + m_2 - 2}$ H_0 is rejected in favor of H_1; otherwise H_0 is retained.

Case 10. Same as Case 8, but $H_o: \mu_1 = \mu_2$ is to be tested against $H_1: \mu_1 \neq \mu_2$ at a significance level of α.

Step 1. Compute $\alpha' = 1 - \frac{\alpha}{2}$

Step 2. Determine $t_{\alpha', m_1 + m_2 - 2}$ using Figure 10-55.

Step 3. Same s Steps 2, 3, and 4 of Case 8.

Step 4. If $r < -t_{\alpha', m_1 + m_2 - 2}$ or if $r > t_{\alpha', m_1 + m_2 - 2}$ reject H_o in favor of H_1; otherwise H_o is retained.

The next level of abstraction in this series of test cases would be the removal of the assumption that the standard deviations of the two populations involved are equal. Unfortunately, this removal leads to a discussion quite beyond the scope of this course. The reader, interested in pursuing this problem, is referred to any standard test on mathematicl statistics. However, using the statisitic, r, where

$$r = \frac{\bar{X}_2 - \bar{X}_1}{\sqrt{\frac{S_1^2}{m_1} + \frac{S_2^2}{m_2}}}$$

and the "Student t" table with + m_2 - 2 degrees of freedom is the customary procedure followed in this case.

The cases involving the student t distribution discussed above have all assumed an initial Normal, $n(x;\mu,\sigma)$ population. (Indeed, for samples of sizes greater than 30, the normal distribution may be used to determine regions of rejection even though σ^2 is estimated from the data). However, the t distribution is applicable in a wide variety of situations in which the underlying population is not Normal.

To illustrate this last statement we consider the following experiment which was repeated 100 times.

All jacks, queens, and kings were removed from a standard deck of cards. The remaining cards, 1 - 10, represented a uniform distribution, $P(x=k) = 1/10$ for $k = 1, \ldots, 10$. A sample of size 5 was drawn from this deck in such a way that the probability of drawing any denomination, (1-10), was the same from draw to draw.

Now, the true mean of the original population was known, $\mu = 5.5$.

The sample of size 5 was used to test $H_0: \mu = 5.5$, against $H_1: \mu \neq 5.5$ at a 10% significance level as follows:

(1) $\alpha' = 1 - \frac{\alpha}{2} = 0.95$

(2) $t_{0.95,4} = 2.132$

(3) $S^2 = \frac{1}{4} \sum_{i=1}^{5} (x_i - \overline{X})^2$

(4) $r = \frac{\overline{X} - 5.5}{S/\sqrt{5}}$

(5) If $r < -2.132$ or $r > 2.132$, H_0 was rejected; otherwise H_0 was accepted.

According to the development of the theory, H_0 should be rejected 10% of the time. In 100 trials the actual number of rejections was 9, i.e., the observed proportion of rejections was 9.0%, a fair degree of approximation since the parent distribution was far from normal and five is a small sample size.

As long as the density function of $\overline{X}$ is fairly symmetric about the mean of the parent density function, the "t test" can be used even though the parent population is not Normal, $n(x;\mu,\sigma)$.

Case 11. A group of m identical items is to be put on trial until all m fail.

Each item is assumed to have a $\lambda e^{-\lambda x}$ density function for time-to-failure. Of course, the values of λ associated with each item are assumed to be equal. $H_0: \lambda = \lambda_0$ is to be tested against $H_1: \lambda < \lambda_0$ at an α level of significance.

Step 1. Enter the χ^2 table with 2m degrees of freedom and with α and determine a value, χ^2, such that $P(\chi^2 < \chi_0^2) = \alpha$ or $P(\chi^2 > \chi_0^2) = 1 - \alpha$.

Step 2. Determine $T_0 = \frac{\chi_0^2}{2\lambda_0}$

Step 3. Calculate, T, where T is the total of the observed times-to-failure for the above m items.

Step 4. If $T < T_0$ reject H_0 in favor of H_1; otherwise retain H_0.

Case 12. Same as Case 10, but now the <u>total operating time</u> of the m trials is fixed in advance to be T_0'.

NOTE: THE TRIAL TIME ASSOCIATED WITH • EACH ITEM IS NOT BEING FIXED IN ADVANCE.

Step 1. The experiment if performed and the number of failures, tk, occurring during the test is noted.

Step 2. A value of χ_0^2, as in Case 10, is determine entering the tables with 2k + 2 degrees of freedom and with the value of α.

Step 3. If $T_0' < \frac{\chi_0^2}{2\lambda_0}$ reject H_0 in favor of H_1; otherwise H_0 is retained.

Case 13. Same as Case 8 but now the experiment is terminated when the kth failure occurs; k is a specified integer. (This is one method of truncating the experiment).

Step 1. Determine χ_0^2 using 2k degrees of freedom and α as was done in Case 10.

Step 2. Compute total operating time, T, of the m items in the test.

$$T = \sum_{i=1}^{k} t_i + (m-k)t_k$$

Step 3. If $T < \frac{\chi_0^2}{2\lambda_0}$ reject H_0 in favor of H_1; otherwise accept H_0.

3. DESIGN OF EXPERIMENTS AND ANALYSIS OF VARIANCE

In a previous chapter we have considered in some general terms a concept called a test plan. In this section we consider specific statistical techniques that may be used within this test plan, in particular that area of statistics called design of experiments and the methodology - analysis of variance - used therein.

Historically, the design of experiments was first used extensively in agricultural experiments. The standard technique of "differences between two means"; i.e., the "t" test had been used together with data from a "treated" and "control" group to determine if the "treatment" really had an effect. However, things got more complicated. Numerous factors such as type of seed, type and amount of fertilizer, amount of water, had to be considered simultaneously. The use of paired comparisons meant inefficient use of resources as well as inefficient production of information based on the data gathered from these tests. With the advent of the development of Design of Experiments and the associated use of Analysis of Variance, a method of making a number of simultaneous comparisons with one testing procedure was available. This method meant not only that the data from a test could be treated more efficiently, but that the test itself could be designed to yield the same information with the use of fewer resources, i.e., the resources were used more efficiently.

There are complete half-year graduate level courses in design of experiments. Clearly, we cannot develop this area so completely here. Therefore, we shall consider only the concepts involved in this discussion.

3.1 APPLICABILITY OF USE OF EXPERIMENTAL DESIGN

Experimental design is used to determine whether or not the effects of "factors" are significant. "Factors" can involve the external environments of operation as humidity, temperature, salt air concentration, etc. "Factors" may also involve the operational conditions of applied voltage, or pressure head, or RPM - as appropriate. Obviously, this technique could be used when it was thought that the effects of such factors on reliability were both strong and deleterious. However, while the design of experiments does represent an efficient means of gaining desired information, its efficiency is directly proportional to the amount of knowledge as to the factors which are possibly important in a particular problem. Use of this technique presumes the absence of the "shotgun approach" to finding "causes" of failure. Thus, the statistician is dependent on the engineer to define the "factors", while the engineer relies on the statistician to provide "efficiency."

As will be seen, the use of this technique can still require a considerable expenditure of time and funds, Therefore, its use in a development program is usually limited to critical hardware items. Furthermore, there should be a reasonable amount of engineering confidence that the possible important factors inducing the problem to be studied has been delineated before such a design is implemented.

Finally, in order to consider a particular "factor" in the design of the experiment, it must be possible to provide a reasonable amount of control over the values that the "factor" may take on during the course of the experiment, i.e., the "factor" values must be reproducible.

3.2 ANALYSIS OF VARIANCE

While the arithmetic associated with analyzing data from experiments that have a complex design can be very complicated, the fundamental arithmetic identity is an extremely simple one. We shall provide an illustration of this identity first.

The general formulation of the arithmetic identity to be used can be written as follows:

$$\sum_{i=1}^{n} (X_i - a)^2 = \left[\sum_{i=1}^{n} (X_i - \bar{X})^2\right] + n(\bar{X} - a)^2$$

Let us see how this equation applies in a rather simple case. There are two sets of observations - each set with four observations. Observation values in the first set are denoted by X_{11}, X_{12}, X_{13}, X_{14}. For our illustration $X_{11} = 1$, $X_{12} = 2$, $X_{13} = 3$, $X_{14} = 4$. The second set of values are $X_{21} = 8$, $X_{22} = 9$, $X_{23} = 10$, and $X_{24} = 11$.

(1) The eight observations considered as a single group has a mean of six and we write $\bar{\bar{X}}$ (the grand or overall mean) = 6.0.

(2) The sum of the six squared deviations from this "grand mean" of 6.0 is 108.0, i.e.,

$$\sum_{j=1}^{2} \sum_{i=1}^{4} (X_{ij} - \bar{\bar{X}})^2 = 108.0.$$

This sum of overall observations of the squared deviations from the grand mean is called the "Total Sum of Squares".

(3) The mean in the first group is $\bar{X}_1 = 2.5$ and in the second group the mean is $\bar{X}_2 = 9.5$. Now, $\sum_i n(\bar{X}_i - \bar{\bar{X}})^2$ is called the "between group" sum of squares.

The value of this "between group" sum of squares is the value of $4(2.5 - 6)^2 + 4(9.5 - 6)^2 = 4 \; [(3.5)^2 + (-3.5)^2]$ $= 4 \; [12.25 + 12.25] = 4 \; [24.5] = 98.0$.

(4) Considering the first group of four observations as a unit, they have a mean of 2.5 and the sum of squared deviations from this group mean is 5.0. This is the "within group" sum of squares for the first group. The second group has a mean of 9.5 and a "within group" sum of squares of 5. The total "within group" sum of squares is, then, 5 + 5 or 10.

(5) The total sum of squares, 108, has thus been partitioned into (a) the "between group" sum of squares 98.0, and (b) the "within group" sum of squares of 10.

$$\sum_{i=1}^{2} \left(\sum_{j=1}^{4} \{X_{ij} - \bar{\bar{X}}\}^2 \right) = \left[\sum_{i=1}^{2} \left\{ \sum_{j=1}^{4} (X_{ij} - \bar{X}_i)^2 \right\} \right] + 4 \sum_{i=1} (X_i - \bar{\bar{X}})^2$$

or, in general,

$$\sum_{i=1}^{k} \left(\sum^{n_i} \{ X_{ij} - \bar{\bar{X}} \}^2 \right) = \left[\sum_{i=1}^{k} \left\{ \sum_{j=1}^{n_i} (X_{ij} - \bar{X})^2 \right] + \sum_{i=1}^{k} n_i (\bar{X}_i - \bar{\bar{X}})^2$$

where there are k different groups, n_i observations in the i^{th} group, $\bar{\bar{X}}$ is the grand mean and $\bar{X}_i$ is the mean in the i^{th} group.

As a final note, the total "within group" sum of squares is sometimes referred to as the experimental error.

3.3 THE BASIC DESIGN OF EXPERIMENTS MODEL

A One Factor Experiment

For the purposes of this discussion it shall be assumed that we have n observations in each of k groups - a total of n x k observations. The n specimens in a group might be n transistors operating at a common ambient temperature. The differences between the groups are different ambient temperatures. (In standard terminology - the different groups represent different treatments). The observations might be times-of-failure.

It is assumed that the observation, X_{ij}, associated with the j^{th}

specimen in the i^{th} group can be written as

$$X_{ij} = \mu + b_i + e_{ij}$$

where μ is called the true overall mean, b_i is called the true treatment effect and e_{ij} is the deviation of the observation from the true group mean, $\mu + b_i$. It is furthermore, understood that μ is such that

$$\sum_{i=1}^{k} b_i = 0.$$

Now, the overall sample mean, $\bar{\bar{X}}$, is an estimator for μ; the sample group mean, $\bar{X}_i$, is an estimator for $\mu + b_i$, thus, $\bar{X}_i - \bar{\bar{X}}$ is an estimator for b_i.

It is now assumed that the e_{ij} all represent independent observations from the <u>same</u> Normal density function $n(X_i;\ 0,\ \sigma)$. The fact that e_{ij}'s are independent implies that (1) repair does not influence the time-to-the-next-failure and (2) wear-out is not a factor in the successive failures. The assumption that the e_{ij}'s come from the same density function, $n(X;\ 0,\ \sigma)$, is used as follows.

Now, $X_{ij} - \bar{X}_i = (\mu + b_i + e_{ij}) - (\mu + b_i + e_i') = e_{ij} - e_i'$ where e_i' is the deviation of $\bar{X}_i$ from $\mu + b_i$. (Note e_i' is a function of $e_{i1}, e_{i2} \ldots e_{i,n}$ for each value of i.).

Thus, $\sum_{i=1}^{k} \left\{ \sum_{j=1}^{n} (X_{ij} - \bar{X}_i)^2 \right\}$ is a function only of the e_{ij}'s. This "within group" sum of squares, then, may be used to estimate σ^2.

Now, $\bar{X}_i - \bar{\bar{X}} = \mu + b_i + e_i' - (\mu + e'')$ or $\bar{X}_i - \bar{\bar{X}} = b_i + (e_i' - e'')$ where e'' is a function of all the e_{ij}. Thus

$$n\sum_{i=1}^{k} (\bar{X}_i - \bar{\bar{X}})^2 = n\sum_{i=1}^{k} (b_i + e_i' - e'')^2$$

This "between group" sum of squares therefore involves the b_i's and the e_{ij}'s.

The null hypothesis in this design is that all the b_i's are equal to zero. Under the null hypothesis, the "between group" sum of squares,

$$n\sum_{i=1}^{k} (\bar{X}_i - \bar{\bar{X}})^2 = n\sum_{i=1}^{k}(b_i + e_i' - e'')^2 \text{ becomes } n\sum_{i=1}^{k}(e_i' - e'')^2,$$

which is a function of the e_{ij}'s only. Indeed, under the null hypothesis the "between group" sum of squares can also be used to estimate σ^2.

Let S_1^2 denote the estimate of σ^2 using the "within group" sum of squares. Let S_1^2 denote the (independent of S_1^2) estimate of σ^2 using the "between group" sum of squares. Under the null hypothesis, the ratio, S_2^2/S_1^2, represents the ratio of two independent estimates of the same quantity, σ^2. The ratio should have values close to 1.

On the other hand, if the null hypothesis is not true, i.e., at least one of the b_i's is not zero, then S_2^2 should be greater than S_1^2. Thus, the region of rejection of the null hypothesis is $S_2^2/S_1^2 > F_0$ where the constant, F_0, has to be determined. The manner of determining this value of F_0 and the means of converting the "within group" and "between group" sums of squares to estimates of σ^2 will be discussed in the next section, the F Test.

3.4 THE F TEST

We shall summarize the discussion of the previous section by an analysis-of-variance table for a one factor experiment. The first two columns represent the partitioning of the total sum of squares. The third column, degrees of freedom, is a divisor which converts each of the sum-of-squares parts to an estimator for σ^2. The last column represents the observed value of the F-ratio. (see table 10.2).

To obtain the critical value, F_0, such that the null hypothesis is rejected if $S_2^2/S_1^2 > F_0$, the F table, here presented in Figure 10-55 is used. Three values are required to enter this table. One is the number of degrees of freedom, m, associated with the numerators, S_2^2. Here, m is k - 1. The second is the number of degrees of freedom, N, associated with the denominator, S_1^2. In this case N = i x (n-1). The third is the significance level, α. In Figure 10-55 entry is made using 1 - α.

To illustrate this particular case we consider four groups, G_1, G_2, G_3, G_4, with 3 observations in each group

ANALYSIS OF VARIANCE FOR ONE-FACTOR EXPERIMENT

Column Number

(1) Source of Sum of Squares	(2) Formula	(3) Degrees of Freedom	S_1^2 $\frac{(2)}{(3)}$	F Ratio
Within Cells	$n \sum_{i=1}^{k} \left\{ \sum_{j=1}^{n} (X_{ij} - \bar{X})^2 \right\}$	$k\ (n-1)$	$S_1^2 = \frac{\sum_{i=1}^{k} \left\{ \sum_{j=1}^{n} (X_{ij} - \bar{X}_i)^2 \right\}}{k\ (n-1)}$	
Between Cells	$n \sum_{i=1}^{k} (\bar{X}_i - \bar{\bar{X}})^2$	$k - 1$	$S_2^2 = \frac{n \sum_{i=1}^{k} (\bar{X}_i - \bar{\bar{X}})^2}{k - 1}$	S_2^2 / S_1^2
Total	$\sum_{i=1}^{k} \sum_{j=1}^{n} (X_{ij} - \bar{\bar{X}})^2$	$n\ k - 1$		

	G_1	G_2	G_3	G_4
	2	3	4	5
	3	4	5	6
	4	5	6	7
TOTAL	9	12	15	18
MEAN	3	4	5	6

$$\bar{\bar{X}} = \frac{9+12+15+18}{12} = \frac{54}{12} = 4.5$$

(a) The total sum of squares, $\sum\sum(X_{ij} - \bar{\bar{X}})^2$, can be computed by the formula

$$\sum\sum(X_{ij} - \bar{\bar{X}})^2 = \sum\sum X_{ij}^2 - \frac{T^2}{n\ k}$$

Where T is the grand total of all the observations.

$$\sum\sum X_{ij}^2 = 4 + 9 + 16 + 9 + 16 + 25 + 16 + 25 + 36 + 25 + 36 + 49 = 266$$

$$\frac{T^2}{n\ k} = \frac{(9 + 12 + 15 + 18)^2}{12} = \frac{(54)^2}{12} = \frac{27 \times 27}{3} = 9 \times 27 = 243$$

(a-1) Total SS (sum of squares) = 266 - 243 = 23

(a-2) Number of degrees of freedom = 11

(b) Within group SS

For each of the four groups, $\sum(X_{ij} - \bar{X}_i)^2 = 2$

Total for the four groups is 8.

(b-1) Within Group SS = 8

(b-2) Number of degrees of freedom = k x (n-1) = 4 x 2 = 8

(c) Between Group SS

$$n\left[\sum(\bar{X}_i - \bar{\bar{X}})^2\right] = 3 \times \left[(3 - 4.5)^2 + (4 - 4.5)^2 + (5 - 4.5)^2 + (6 - 4.5)^2\right]$$

$$= 3 \times \left[(0.5)^2 + (1.5)^2 + (1.5)^2 + (0.5)^2 \right]$$

$$= 3 \times \left[0.25 + 2.25 + 2.25 + 0.25 \right] = 3 \times 5 = 15$$

(c-1) Between group SS = 15

(c-2) Number of degree of freedom = m = k - 1 = 3

The analysis-of-variance table (10.2) then takes the form:

Source	Sum of Squares	Degrees of Freedom	S_1^2	F
"Between Cells"	15	3	$S_2^2 = \frac{15}{3} = 5$	$\frac{S_2^2}{S_1^2} = 5$
"Within Cells"	8	8	$S_1^2 = \frac{8}{8} = 1$	
Total	23	11		

Entering the F table with m = 3, N = 8, and 0.90 (a significance level of 10%), the critical value of F, F_c, is found to be 2.92. Since F = 5 > 2.92, the null hypothesis is rejected and treatment effects are said to be significant. The determination of the numerical magnitude of this effect is made using the treatment or group means.

Here, one can see that four treatments are being compared at the same time.

3.5 THE TWO FACTOR EXPERIMENT

The discussion of this type of experiment is included as an illustration of the manner by which complications are introduced. Furthermore, we can take this opportunity to introduce some more of the "design of experiments" terminology.

This type of design is, obviously, used when there are two important factors which are suspected as "causes of failures" in a particular problem. Such combinations as humidity and ambient temperature, pressure head and fluid density, voltage and age of equipment, or, even time of day and route. (This latter set of conditions applies to designing an experiment undertaken to determine the "effects" of departure time and route used on the time to get from work to home). Arbitrarily, we shall call one factor "treatments" and the second factor "environments". The different "treatments" shall be denoted by capital letters, A, B, etc., and the "environments" by numerical subscripts $B_1, B_2, \ldots,$ etc. Specimens are assigned "at random" to the different "treatment-environment" combinations and observations are recorded.

We shall assume that there are an equal number, n, of observations from each "treatment/environment" combination. The letter "r" shall denote the number of different treatments and the letter "s" shall denote the number of environments.

The model is that

$$X_{\alpha i j} = \mu + T_\alpha + b_i + v_{\alpha i} + e_{\alpha i j}$$

where

(1) μ is the true overall mean;

(2) t_α is the "main effect" of treatment α and

$$\sum_{\alpha} t_\alpha = 0$$

where the summation is over the r different treatments;

(3) b_i is the "main effect" of the i^{th} environment and

$$\sum_{i=1}^{s} b_i = 0$$

(4) all the $e_{\alpha i j}$ represent sample values from a $n(x;0,\sigma)$ population;

(5) the $v_{\alpha i}$ are called the "interaction between the "treatments" and the "environments" and

$$\sum_{i=1}^{s} v_{\alpha i} = 0 \text{ for each } \alpha \text{ treatment and}$$

$$\sum_{\alpha} v_{\alpha i} = 0 \text{ for block } i.$$

$$= 3 \times \left[(0.5)^2 + (1.5)^2 + (1.5)^2 + (0.5)^2\right]$$

$$= 3 \times \left[0.25 + 2.25 + 2.25 + 0.25\right] = 3 \times 5 = 15$$

(c-1) Between group SS = 15

(c-2) Number of degree of freedom = m = k - 1 = 3

The analysis-of-variance table (10.2) then takes the form:

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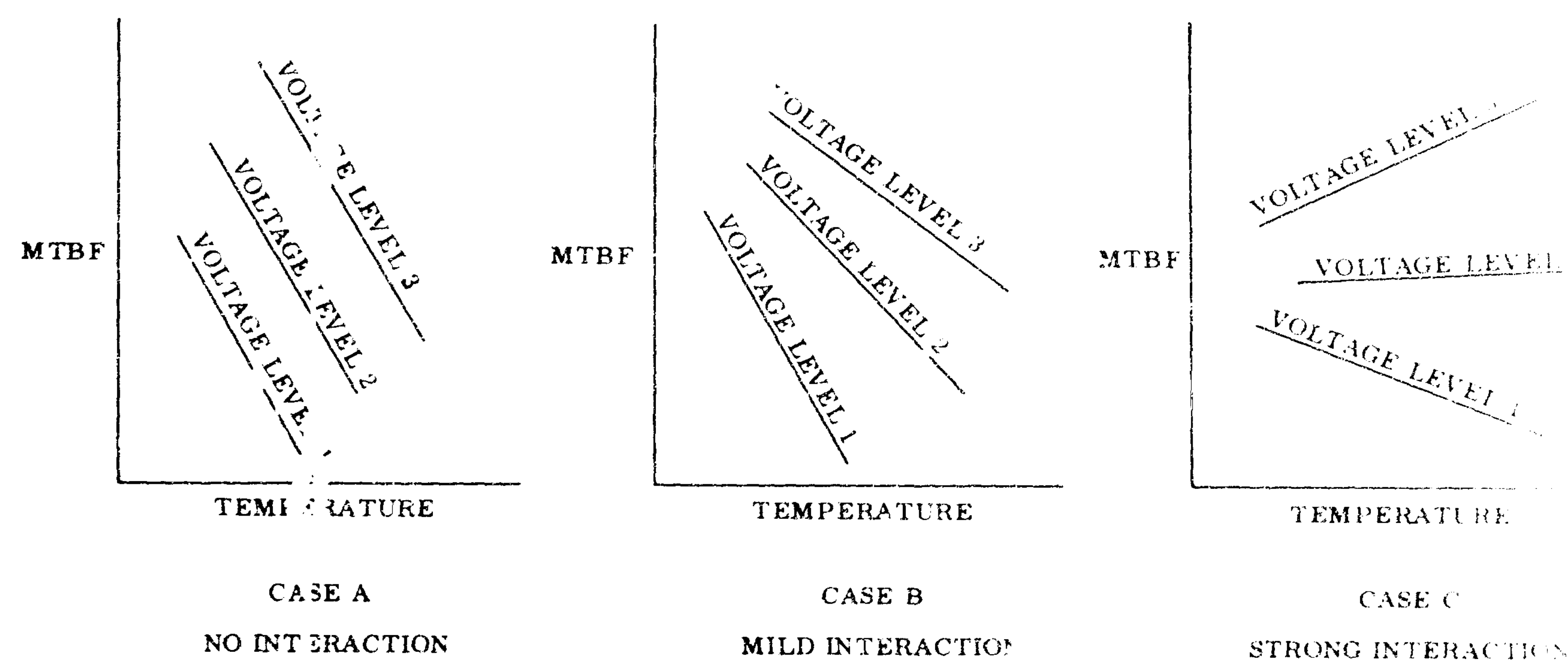
REGRESSION ANALYSIS



These "interaction" terms represent either "reinforcement" or "counteraction" of the effect of either the "treatment" or the block by the other. The graphical presentations in Figure 10-41 where Temperature represents "environments" and Voltage Levels represent "treatments", illustrates different possible situations that might arise.

Again, $\bar{\bar{X}} = \dfrac{T}{n\ s\ r}$ is an estimate for μ;

$\bar{X}_A = \dfrac{T_A}{n\ s}$ is an estimate for $\mu + t_A$:

$\bar{X}_1 = \dfrac{T_1}{n\ r}$ is an estimate for $\mu + b_1$;

$\bar{X}_{A1} = \dfrac{1}{n}\sum_{j=1}^{n} X_{A1j}$ is an estimate for $\mu + t_A + b_1 + \gamma_{A1}$

$\bar{X}_{A1} - \bar{X}_A$ is an estimate for $b_1 + \gamma_{A1}$

$\bar{X}_{A1} - \bar{X}_A - \bar{X}_1$ is an estimate for $\gamma_{A1} - \mu$

$\bar{X}_{A1} - \bar{X}_A - \bar{X}_1 + \bar{\bar{X}}$ is an estimate for γ_{A1}

The total sum of squares, $\sum_{\alpha} \sum_{i=1}^{s} \sum_{j=1}^{n} \{X_{\alpha ij} - \bar{\bar{X}}\}^2$, is now partitioned amongst the four sources:

(1) "Between treatments" Sum of Squares

$$\sum_{\alpha} (\bar{X}_{\alpha} - \bar{\bar{X}})^2$$

(2) "Between environments" Sum of Squares

$$\sum_{i=1}^{s} (\bar{X}_i - \bar{\bar{X}})^2$$

(3) "Interaction" Sum of Squares

$$\sum_{\alpha} \sum_{i=1}^{s} (\bar{X}_{\alpha i} - \bar{X}_{\alpha} - \bar{X}_i + \bar{\bar{X}})^2$$

ANALYSIS OF VARIANCE FOR TWO-FACTOR EXPERIMENT

Source	Sum of Squares	Degrees of Freedom	Estimator for σ^2	F Ratio
Between Treatments	$S_T = n \times s \sum_{\alpha} (\bar{X}_\alpha - \bar{\bar{X}})^2$	$r - 1$	$S_4 = \frac{S_T}{r-1}$	$\frac{S_4}{S_1}$
Between Blocks	$S_B = n \times r \sum_{i=1}^{s} (\bar{X}_i - \bar{\bar{X}})^2$	$s - 1$	$S_3 = \frac{S_B}{s-1}$	$\frac{S_3}{S_1}$
Interactions	$S_I = n \times \sum_{\alpha} \sum_{i=1}^{s} (\bar{X}_{\alpha i} - \bar{X}_\alpha - \bar{X}_i + \bar{\bar{X}})^2$	$(r-1)(s-1)$	$S_2 = \frac{S_I}{(r-1)(s-1)}$	$\frac{S_2}{S_1}$
Within Cells	$S_{WC} = \sum_{\alpha} \sum_{i=1}^{s} \left\{ \sum_{j=1}^{n} (X_{\alpha ij} - \bar{X}_{\alpha i})^2 \right\}$	$r\,s\,(n-1)$	$S_1 = \frac{S_{WC}}{r\,s\,(n-1)}$	
Total	$S = \sum_{\alpha} \sum_{i=1}^{s} \left\{ \sum_{j=1}^{n} \left[X_{\alpha ij} - \bar{\bar{X}} \right]^2 \right\}$	$(r\,s\,n) - 1$		

4. BOOLEAN ALGEBRA

4.1 TECHNIQUES

Boolean algebra is the science of symbols and their combinations used to describe and represent mathematical functions according to the rules of logic. It was named for an English mathematician. George Boole, who, more than a century ago, translated the rules of formal logic into mathematical terms. This science is based upon three fundamental ideas; (a) symbols are used to represent logical operations. (b) these operations are governed by the rules of logic, and (c) these rules are the same as those for an algebra of the numbers 0 and 1 (binary algebra). There are many forms of Boolean algebra: any combination of propositions, each of which is of a binary nature, can be represented by Boolean algebra. This dicussion is designed to familiarize the reader generally with the symbolic logic used in Boolean algebra; illustrations are given of basic logical operations, as well as the symbols used for representing these operations, and methods of combining the symbols into sequences of logical operations.

Using Boolean techniques, the technologist can analyze or synthesize switching systems in any medium. The procedures apply equally well to relays, switches, valves, clutches, flip-flops, transistors, saturable reactions, in fact, any system or "ON-OFF" or binary device is amenable to this logic design technique.

There are as yet no standard symbols for Boolean Algebra functions. The logic literature varies widely in this respect. This section presents some of the symbols and word definitions in common use.

Boolean facilitates the reduction of a problem to simplest form for efficient processing by digital equipment. Functions can be substituted and redundancies eliminated by analysis in Boolean form. As in any algebra, it is necessary to know the characteristics of all terms before the problem can be simplified.

Anything capable of being described can be assigned to classes. Conversely, classes can be used for description. Anything can be described by the classes with which it is or is not identified. The classes can range from so exclusive as to contain nothing, to so general as to include everything. A class containing nothing is called a null class (usually identified by the figure 0); a class including everything is called an all-inclusive class. All classes between these extremes may be identified by letters.

A total concept, usually identified by the figure 1, is the aggregate of all classes. The following example will serve to illustrate the relationship between the total concept, and the all-inclusive, null, and intermediate classes. Horses can be a total concept. Horses can be referred to as being mammals, as being brown, or as being in the State of Maine. Mammals would be an all-inclusive class because it includes all horses. Brown horses would be an intermediate class identified by the letter "A". Horses in the State of Maine would be another restrictive class identified by the letter "B". The null class is arbitrarily designated as that class which is so restrictive as to contain no horses.

With each concept, logical operations can be performed on classes. The three most common logical operations are union, intersection, and complementation. Table 10.4 shows several symbolic representations of each. Union combines classes on an alternative basis and is expressed as "or". For example, the union of the two classes ("A" and "B") cited above, would be expressed as class A "or" class B. This would be less restrictive than either class because it now admits all brown horses and, also, horses of any color in the State of Maine.

Intersection combines classes on a more restrictive basis and is expressed as "and". For example, the intersection of class A and class B would be expressed as A "and" B, and all the requirements of both A and B must be satisfied. Thus the intersection of A and B would specify brown horses in the State of Maine.

Complementation is the operation in which items are described by signifying that they do not belong to a class or classes. For example, horses that are not in class A would include all horses that are not brown. Horses that are not in class A and not in class B would include all horses that are not brown and not in the State of Maine. If this example were expressed as not in class A or not in class B, it would include horses in either, or none, of the classes, but not in both.

Using horses as an example serves to acquaint the reader with the logic of the all-inclusive and null classes, and the operations of union, intersection, and complementation. Figure 10-47 illustrates these operations used in connection with switching networks, and includes symbols that replace the "ands", "ors", and "nots". Referring to Figure 10-47, when the concept is conductivity between terminals X and Y, any condition which completes the circuit between X and Y is an all-inclusive class. Because we are dealing with a binary algebra, there can only be complete conduction or no conduction. With switch A and switch B in series,

TYPICAL BOOLEAN NOTATIONS

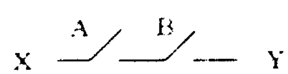
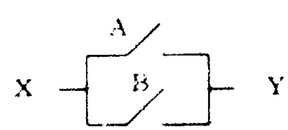
UNION	$\cup$	$+$	$\vee$	$\vee$
INTERSECTION	$\cap$	$\cdot$	$\&$	$\wedge$
COMPLEMENTATION	$-$	$'$	$\sim$	$\urcorner$

LOGICAL FUNCTIONS

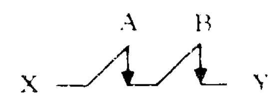
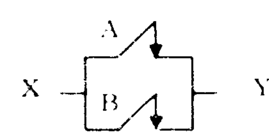
EXCLUSIVE "OR"	$\Leftrightarrow$	$\not\equiv$	
EQUIVALENCE	$\Leftrightarrow$	$\equiv$	$\rightleftarrows$
IMPLICATION	$\Rightarrow$	$\supset$	$\rightarrow$
REVERSE IMPLICATION	$\Leftarrow$	$\subset$	$\leftarrow$
INHIBITION	$\not\Rightarrow$	$\not\supset$	

SWITCHING CIRCUITRY

RESISTIVITY

SWITCH POSITION	INFINITELY RESISTIVE	CONDUCTIVE
	$A \cup B$	$\bar{A} \cap \bar{B}$
	$A \cap B$	$\bar{A} \cup \bar{B}$

CONDUCTIVITY

SWITCH POSITION	CONDUCTIVE	NON-CONDUCTIVE
	$A \cap B$	$\bar{A} \cup \bar{B}$
	$A \cup B$	$\bar{A} \cap \bar{B}$

both A and B must be in the closed position for the circuit to be conductive. The circuit is not conductive if either A or B is open, or, as expressed in Figure 10-47, A is not closed or B is not closed. With the two switches in parallel, either A or B must be closed (both may be closed) to make the circuit conductive; but both A and B must be open (not closed) to make the circuit not conductive. If the concept were infinite resistance, the all-inclusive and null classes would be reversed. Now, infinite resistance is an all-inclusive class and conductivity is a null class. The switch positions and descriptions are changed as indicated in the figure.

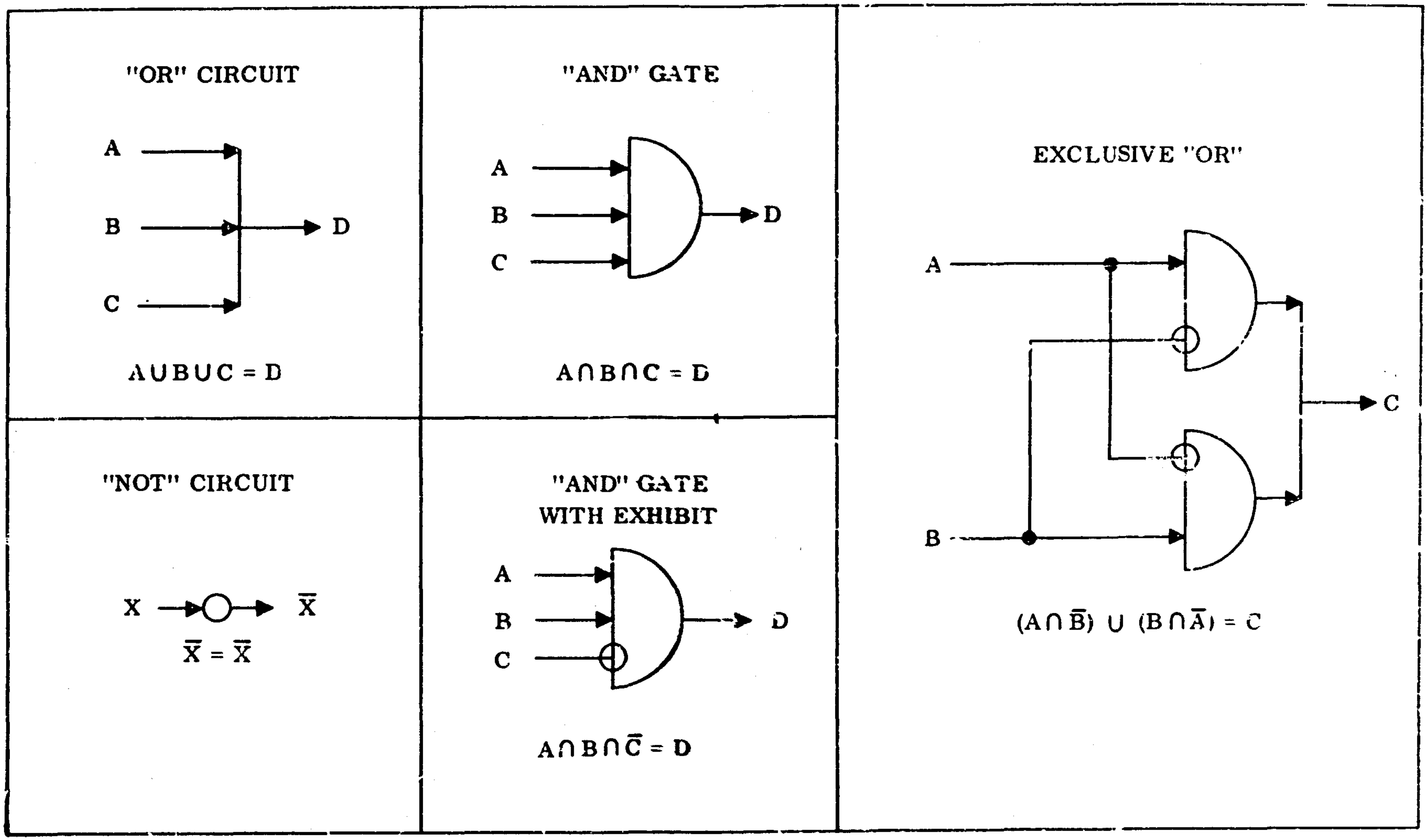
Table 10.5 indicates other logical operations and connectives and a few of the symbols commonly used to represent them. "Exclusive or" elements beong to one but no more than one of the combined terms. "Equivalence" is defined as that relationship between two or more sequences of operations whose resultants are identical. For example, if $A \cap B = C$ and $D \cap E = C$, then $A \cap B$ is equivalent to $D \cap E$. Implication is used when one situation implies another, such as a football game implying running or bodily contact, an electrical output from a circuit implying an input, or a current flow implying a complete circuit. Reverse implication is implication in which the implied term appears first for convenience of expression; for example, $A \supset B$ could be written $B \supset A$. The symbol for inhibition is another method for representing "and not" -- thus inhibition can be defined in terms of the combination of the previously described complementation and intersection.

For each logical function of even the most complex binary device, the combination of inputs and resulting output can be expressed as a Boolean equation. Figure 10-49 illustrates the Boolean expressions for some basic logical functions.

4.2 CLASSIFICATION LOGIC

Various devices have been developed which sort items according to the classes in which they belong. In all cases the device asks, regarding each pertinent class, "Is the element contained in this class?" Because only two possible answers exist (yes or no), a binary device is capable of selecting all the elements in any class. The choice may be made more exclusive by submitting the selected elements to a succession of inspections involving different classes, or it may be made more inclusive by including elements from two or more classes. The ordinary punched-card sorter is perhaps the most widely used automatic device employing this principle.

BOOLEAN EXPRESSIONS



If the entire population of the United States is taken as a concept, it is possible to select the persons who live in Atlanta, Georgia, weigh between 140 and 160 pounds, have blonde hair, have blue eyes, have criminal records, earn less than $10,000 per year, and own their homes. Of course, the required information must be available and properly recorded for each person. The recording can be in the form of a card for each person, containing discrete spaces to represent up to several hundred classes. Class A may include everyone who lives in Atlanta, Georgia; class B, everyone (in the United States) who weighs between 140 and 160 pounds; class C, everyone having blonde hair; class D, everyone with blue eyes; class E, everyone with a criminal record; class F, everyone who earns less than $10,000 per year; etc. The fact that a person belongs to any class is indicated by a hole punched through that person's card in the space representing that class.

A machine capable of inspecting one class at a time must be successively set up to sort out the cards which have a hole in the space representing each pertinent class. The inspection can be by means of mechanical pins, light rays, air pressure (player pianos inspect the roll to determine which notes are to be played), electrical contacts, etc. Only the selected cards need be inspected in succeeding operations. Note that the machine is performing the logical operation of intersection ($A \cap B \cap C \cap D \cap E \cap F \cap G$).

The order of sorting is unimportant except that the total number of inspections can be reduced by sorting for the most restrictive class first. Repetitive sorting for a single class always results in selection of the same cards, so $A \cap A = A$, or $2A = A$. It is evident, then, that numerical coefficients have no meaning in Boolean algebra. Fairly simple machines can inspect several classes simultaneously and select only those cards which fit all the classes being inspected.

It is usually more practical to divide detailed information such as weight and income into several subclasses for recording. The number and range of the classes are fixed according to the detail of the available information and the purposes for which it is to be used. Weight may be classed as (B_1) less than 100 pounds, (B_2) 100 to 120 pounds, (B_3) 120 to 130 pounds, (B_4) 130 to 140 pounds, (B_5) 140 to 150 pounds, (B_6) 150 to 160 pounds, (B_7) 160 to 170 pounds, (B_8) 170 to 180 pounds, (B_9) 180 to 200 pounds, and (B_{10}) over 200 pounds. Income may be classed as (F_1) 0 to $2,000, ($F_2$) $2,000 to $4,000, ($F_3$) $4,000 to $6,000, ($F_4$) $6,000 to $8,000 ($F_5$) $8,000 to $10,000, ($F_6$) $10,000 to $15,000, and ($F_7$) over $15,000.

The sorting machine, in order to select a weight class from 140 to 160 pounds, must be set to select those cards punched for either weight subclass B_5 or B_6. In doing this, the machine is performing the Boolean operation of union $(B_5 \cup B_6)$. To select the "under $10,000" income class, the machine must choose either (1) all the cards punched for income classes F_1, F_2, F_3, F_4, or F_5, or (2) those cards which are not punched for class F_6 and not punched for class F_7. The latter method may be more desirable because it requires inspection of only two spaces instead of five spaces. When the machine is set up to select cards which are not punched, it is performing the logical operation of complementation. "Not F_6 and not F_7," is expressed ideographically as $\overline{F_6} \cap \overline{F_7}$.

The expression $A \cap (B_5 \cup B_6) \cap C \cap D \cap E \cap (\overline{F_6} \cap \overline{F_7})$ is the original example with the term $(B_5 \cup B_6)$ substituted for class B, and the term $(\overline{F_6} \cap \overline{F_7})$ substituted for class F. To avoid possible ambiguities, the new terms are isolated in parentheses. The parentheses, like the punctuation marks in ordinary language, are used to group related terms. The logical rules of manipulation for parentheses in Boolean algebra become obvious when the expressions are converted to ordinary language. The expression $A \cap (B_5 \cup B_6) \cap C$ concisely states "A, and B_5 or B_6, and C." Omission of the parentheses, $A \cap B_5 \cup B_6 \cap C$, like omission of punctuation marks, "A and B_5 or B_6 and C," results in ambiguity. Parentheses, or punctuation marks, are necessary in this case to prevent misinterpreting the expression as "A and B_5, or B_6 and C.".

The expression $E \cap (\overline{F_6} \cap \overline{F_7})$ states "E, and not F_6 and not F_7." Note the the punctuation may be omitted without causing ambiguity in this case, and $E \cap (\overline{F_6} \cap \overline{F_7}) = E \cap \overline{F_6} \cap \overline{F_7}$. Within any Boolean expression, changes of signs from $\cap$ to $\cup$ or vice versa always require the use of parentheses to avoid ambiguity.

4.3 RULES OF OPERATION

In the example of the card-sorting machine, the function of selecting the cards punched for income classes F_1, F_2, F_3, F_4, or F_5 implied selection of the cards not punched for income class F_6 and not punched for income class F_7; therefore,

$$F_1 \cup F_2 \cup F_3 \cup F_4 \cup F_5 \Rightarrow \overline{F_6} \cap \overline{F_7}$$

and the latter, more convenient expression of two terms was substituted for the five-term expression. In this case, the logical substitution of functions may have been apparent without the use of Boolean algebra but, in the simplification or more complex problems much more maneuvering is often necessary and many manipulations which are obvious and easy in Boolean form might escape detection by direct analysis.

With certain limitations, which will be mentioned later, the operation of union is the same as that of addition in common algebra, and the operation of intersection is the same as that of multiplication. The use of $\cup$ and $\cap$ instead of + and · does not preclude the possibility of contracting the symbolism as is done with + and · in such expressions as, for example, AB+C. The expression $(A\cap B)\cup C$ can be contracted to $AB\cup C$. Further, by adopting the convention that the implied connective is that which does not appear in an expression (and also that the implied connective is accompanied by implied parentheses) both kinds of expressions can be contracted. Thus: $(A\cap B)\cup C$ can be contracted to $AB\cup C$; $(A\cup B)\cap C$ can be contracted to $AB\cap C$: $A\cap(B_5\cup B_6)\cap C$ can be contracted to $A\cap B_5B_6\cap C$; and the expression

$$A\cap(B_5\cup B_6)\cap C\cap D\cap E\cap\overline{F_6}\cap\overline{F_7}$$

can be contracted to either

$$A\cap B_5B_6\cap C\cap D\cap E\cap\overline{F_6}\cap\overline{F_7}$$

or

$$A\;(B_5\cup B_6)C\;D\;E\;\overline{F_6}\;\overline{F_7}.$$

Another method for contracting and simplifying Boolean expressions is to substitute one term of an abviously true relationship for its more complex counterpart. For example, this can be done in the following ten relationships which are true for all classes:

1. $X\cup X=X$; also $X\cap X=X$. A proposition is not changed by repetition, either in an alternative or in a restrictive sense. For this reason, coefficients other than 0 and 1 have no meaning ($2X = X$).

2. $0\cap X=0$. Since an "and" operation is restrictive and no class can be more restrictive than the null class, any intersecting combination which includes a null class (0) must be all exclusive.

3. $X\cap 1=X$. All classes must be entirely contained within the concept; therefore the added restriction of belonging to the concept has no effect.

4. $X \cup 0 \equiv X$. Nothing belong to the null class (0); hence the inclusion of the null class as an alternative is meaningless.

5. $X \cup 1 \equiv 1$. Everything within the concept must belong to any union which includes the entire concept (1) as an alternative. No class can include more than the total concept.

6. $X \cap X \equiv 0$. Nothing can belong to any class and not belong to that class.

7. $X \cup X \equiv 1$. Everything must either beong to a class or not belong to that class.

8. $\overline{(X)} \equiv X$. Double negatives cancel each other.

9. $\overline{(X \cup Y)} \equiv \bar{X} \cap \bar{Y}$. Everything which does not belong to either X or Y obviously does not belong to X and does not belong to Y.

10. $\bar{X} \cup \bar{Y} \equiv \overline{(X \cap Y)}$. That which either does not belong to X or does not belong to Y cannot belong to both X and Y.

As an ordinary algebra, there are various manipulations possible in Boolean algebra which will permit simplification of expression. For example, in ordinary algebra:

$$\frac{a^2 - b^2}{a + b} = \frac{(a + b)\ (a - b)}{a + b} = a - b$$

In Boolean algebra, manipulations based on the following postulates are also possible.

11. Operations of union or intersection are commutative.

$X \cup Y \equiv Y \cup X$ (Compares to $X+Y = Y+X$ in common albegra)
$X \cap Y \equiv Y \cap X$ (Compares to $X \cdot Y = Y \cdot X$ in common algebra,

The example of the card-sorting device showed that the order of inspection has no logical significance.

12. Operations of union or intersection are associative.

$X \cup (Y \cup Z) \equiv (X \cup Y) \cup Z \equiv X \cup Y \cup Z$ (compares to

$X + (Y + Z) = (X + Y) + Z = X + Y + Z$ in common algebra)

$X \cap (Y \cap Z) \equiv (X \cap Y) \cap Z \equiv X \cap Y \cap Z$ (compares to

$$X \cdot (Y \cdot Z) = (X \cdot Z) \cdot Z = X \cdot Y \cdot Z \text{ in common algebra)}$$

Parentheses are required only when a change of connectives occurs.

13. Operations of union and intersection are distributive.

$X \cup (Y \cap Z) = (X \cup Y) \cap (X \cup Z)$ (not true for addition in common algebra)

$X \cap (Y \cup Z) = (X \cap Y) \cup (X \cap Z)$ (compare to

$X \cdot (Y+Z) = (X \cdot Y) + (X \cdot Z)$ in algebra)

Everything which is included either in X or in both Y and Z must be included in X or Y and in X or Z. Everything which is included in X and either Y or Z must be included either in X and Y, or in X and Z.

In the following step by-step simplification of $A \cup \bar{A}B$ to $A \cup B$, the manipulation performed is explained beside each step, the circled numbers refer to the rules of operation given above.

$A \cup \bar{A}B = A(B \cup \bar{B}) \cup \bar{A}B$	$(B \cup \bar{B}) = 1$ (7), $A \cap 1 = A$ (3)
$= AB \cup A\bar{B} \cup \bar{A}B$	$A \cap (B \cup \bar{B}) = AB \cup A\bar{B}$ (13)
$= AB \cup A\bar{B} \cup \bar{A}B \cup AB$	$AB \cup AB = AB$ (1)
$= A(B \cup \bar{B}) \cup \bar{A}B \cup AB$	$AB \cup A\bar{B} = A(B \cup \bar{B})$ (13)
$= A(B \cup \bar{B}) \cup B(\bar{A} \cup A)$	$\bar{A}B \cup AB = B(\bar{A} \cup A)$ (13)
$= A(B \cup \bar{B}) \cup B$	$(\bar{A} \cup A) = 1$ (7), $B \cap 1 = B$ (3)
$= A \cup B$	$(B \cup \bar{B}) = 1$ (7), $(A \cap 1) = A$ (3)
$A \cup \bar{A}B = A \cup B$	

5. REFERENCES

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$$F(t) = \int_{-\infty}^{t} \frac{\left(\frac{n-1}{2}\right)!}{\left(\frac{n-2}{2}\right)! \sqrt{\pi n} \left(1 + \frac{x^2}{n}\right)^{(n+1)/2}} dx$$

n \ F	.75	.90	.95	.975	.99	.995	.9995
1	1.000	3.078	6.314	12.706	31.821	63.657	636.619
2	.816	1.886	2.920	4.303	6.965	9.925	31.598
3	.765	1.638	2.353	3.182	4.541	5.841	12.941
4	.741	1.533	2.132	2.776	3.747	4.604	8.610
5	.727	1.476	2.015	2.571	3.365	4.032	6.859
6	.718	1.440	1.943	2.447	3.143	3.707	5.959
7	.711	1.415	1.895	2.365	2.998	3.499	5.405
8	.706	1.397	1.860	2.306	2.896	3.355	5.041
9	.703	1.383	1.833	2.262	2.821	3.250	4.781
10	.700	1.372	1.812	2.228	2.764	3.169	4.587
11	.697	1.363	1.796	2.201	2.718	3.106	4.437
12	.695	1.356	1.782	2.179	2.681	3.055	4.318
13	.694	1.350	1.771	2.160	2.650	3.012	4.221
14	.692	1.345	1.761	2.145	2.624	2.977	4.140
15	.691	1.341	1.753	2.131	2.602	2.947	4.073
16	.690	1.337	1.746	2.120	2.583	2.921	4.015
17	.689	1.333	1.740	2.110	2.567	2.898	3.965
18	.688	1.330	1.734	2.101	2.552	2.878	3.922
19	.688	1.328	1.729	2.093	2.539	2.861	3.883
20	.687	1.325	1.725	2.086	2.528	2.845	3.850
21	.686	1.323	1.721	2.080	2.518	2.831	3.819
22	.686	1.321	1.717	2.074	2.508	2.819	3.792
23	.685	1.319	1.714	2.069	2.500	2.807	3.767
24	.685	1.318	1.711	2.064	2.492	2.797	3.745
25	.684	1.316	1.708	2.060	2.485	2.787	3.725
26	.684	1.315	1.706	2.056	2.479	2.779	3.707
27	.684	1.314	1.703	2.052	2.473	2.771	3.690
28	.683	1.313	1.701	2.048	2.467	2.763	3.674
29	.683	1.311	1.699	2.045	2.462	2.756	3.659
30	.683	1.310	1.697	2.042	2.457	2.750	3.646
40	.681	1.303	1.684	2.021	2.423	2.704	3.551
60	.679	1.296	1.671	2.000	2.390	2.660	3.460
120	.677	1.289	1.658	1.980	2.358	2.617	3.373
∞	.674	1.282	1.645	1.960	2.326	2.576	3.291

Upper 10% Points of the F Distribution Table of $F_{.10}(d_1, d_2)$

Degrees of freedom for the numerator (d_1)

Degrees of freedom for the denominator (d_2)	1	2	3	4	5	6	7	8	9	10	15	20	30	50	100	200	500	∞
1	39.9	49.5	53.6	55.8	57.2	58.2	58.9	59.4	59.9	60.2	61.2	61.7	62.3	62.7	63.0	63.2	63.3	63.3
2	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39	9.42	9.44	9.46	9.47	9.48	9.49	9.49	9.49
3	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24	5.23	5.20	5.18	5.17	5.15	5.14	5.14	5.14	5.13
4	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92	3.87	3.84	3.82	3.80	3.78	3.77	3.76	3.76
5	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32	3.30	3.24	3.21	3.17	3.15	3.13	3.12	3.11	3.10
6	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94	2.87	2.84	2.80	2.77	2.75	2.73	2.73	2.72
7	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70	2.63	2.59	2.56	2.52	2.50	2.48	2.18	2.47
8	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54	2.46	2.42	2.38	2.35	2.32	2.31	2.30	2.29
9	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44	2.42	2.34	2.30	2.25	2.22	2.19	2.17	2.17	2.16
10	3.28	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35	2.32	2.24	2.20	2.13	2.12	2.09	2.07	2.06	2.06
11	3.23	2.86	2.66	2.54	2.45	2.39	2.34	2.30	2.27	2.25	2.17	2.12	2.08	2.04	2.00	1.99	1.98	1.97
12	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19	2.10	2.06	2.01	1.97	1.94	1.92	1.91	1.90
13	3.14	2.76	2.56	2.43	2.35	2.28	2.23	2.20	2.16	2.14	2.05	2.01	1.96	1.92	1.88	1.86	1.85	1.85
14	3.10	2.73	2.52	2.39	2.31	2.24	2.19	2.15	2.12	2.10	2.01	1.96	1.91	1.87	1.83	1.82	1.80	1.80
15	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.06	1.97	1.92	1.87	1.83	1.79	1.77	1.76	1.76
16	3.05	2.67	2.46	2.33	2.24	2.18	2.13	2.09	2.06	2.03	1.94	1.89	1.84	1.79	1.76	1.74	1.73	1.72
17	3.03	2.64	2.44	2.31	2.22	2.15	2.10	2.06	2.03	2.00	1.91	1.86	1.81	1.76	1.73	1.71	1.69	1.69
18	3.01	2.62	2.42	2.29	2.20	2.13	2.08	2.04	2.00	1.98	1.89	1.84	1.78	1.74	1.70	1.68	1.67	1.66
19	2.99	2.61	2.40	2.27	2.18	2.11	2.06	2.02	1.98	1.96	1.86	1.81	1.76	1.71	1.67	1.65	1.64	1.63
20	2.97	2.59	2.38	2.25	2.16	2.09	2.04	2.00	1.96	1.94	1.84	1.79	1.74	1.69	1.65	1.63	1.62	1.61
22	2.95	2.56	2.35	2.22	2.13	2.06	2.01	1.97	1.93	1.90	1.81	1.76	1.70	1.65	1.61	1.59	1.58	1.57
24	2.93	2.54	2.33	2.19	2.10	2.04	1.98	1.94	1.91	1.88	1.78	1.73	1.67	1.62	1.58	1.56	1.54	1.53
26	2.91	2.52	2.31	2.17	2.08	2.01	1.96	1.92	1.88	1.86	1.76	1.71	1.65	1.59	1.55	1.53	1.51	1.50
28	2.89	2.50	2.29	2.16	2.06	2.00	1.94	1.90	1.87	1.84	1.74	1.69	1.63	1.57	1.53	1.50	1.49	1.48
30	2.88	2.49	2.28	2.14	2.06	1.98	1.93	1.88	1.85	1.82	1.72	1.67	1.61	1.55	1.51	1.48	1.47	1.46
40	2.84	2.44	2.23	2.09	2.00	1.93	1.87	1.83	1.79	1.76	1.66	1.61	1.54	1.48	1.43	1.41	1.39	1.38
50	2.81	2.41	2.20	2.06	1.97	1.90	1.84	1.80	1.76	1.73	1.63	1.57	1.50	1.44	1.39	1.36	1.34	1.33
60	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74	1.71	1.60	1.54	1.48	1.41	1.36	1.33	1.31	1.29
80	2.77	2.37	2.15	2.02	1.92	1.85	1.79	1.75	1.71	1.68	1.57	1.51	1.44	1.38	1.32	1.28	1.26	1.24
100	2.76	2.36	2.1	2.00	1.91	1.83	1.78	1.73	1.70	1.66	1.56	1.49	1.42	1.35	1.29	1.26	1.23	1.21
200	2.73	2.33	2.11	1.97	1.88	1.80	1.75	1.70	1.66	1.63	1.52	1.46	1.38	1.31	1.24	1.20	1.17	1.14
500	2.72	2.31	2.10	1.96	1.86	1.79	1.73	1.68	1.64	1.61	1.50	1.44	1.36	1.28	1.21	1.16	1.12	1.09
	2.71	2.30	2.08	1.94	1.85	1.77	1.72	1.67	1.63	1.60	1.49	1.42	1.34	1.26	1.18	1.13	1.08	1.00

Chapter 11

VERIFICATION

Chapter 11

VERIFICATION

If all people concerned in the development of hardware for a system were omniscient, there would be no need for a hardware development phase. Engineers could make up specifications and drawings; the hardware would be built, acquired, and installed; and the installed system would work. Unfortunately, real true-to-life human beings are not omniscient. They have to acquire information. The basic purpose of experimenting (testing) with hardware is to provide information which cannot be gained by other means. Thus, when there is the willingness to appreciate the need to spend the money and time to obtain desired information by testing, one has the beginning of a test program.

Testing falls into four general categories:

(a) Development tests - to get the equipment to work and evaluate the characteristics of its performance and endurance under severe environments.

(b) Qualification tests - to formally subject the equipment to its planned operating environment to display the adequacy of the design.

(c) Acceptance tests - to verify that the production lot falls within the specified tolerance range, and

(d) Demonstration tests - to provide an objective evaluation of the capability of the production lot to continue to perform its function under specified environmental and loading conditions.

This course will not dwell on tests and development testing to advance the state-of-the-art but on the verification of performance attainment. The purpose of this chapter is to discuss the applications of testing to the assurance of reliability in the product.

Let us discuss, briefly the decision process. The engineer responsible for a design has the responsibility of providing an equipment that will work when required and will continue to keep working as long as it is needed.

In the process of design, most of the design parameters are determined analytically. In developing his design, the designer makes numerous decisions, based on facts available to him, experience and engineering judgment. The analytical method used has usually been developed and tested in numerous applications. The designer applies engineering judgment to the applicability of that particular analysis to the design he is working on. Factors influencing the ultimate reliability of the equipment are included in the choices he has made. For example, when he computes the structural strength of a foundation, he bases the strength on achieving a low probability of failure of that member and adequate stiffness to prevent excessive deflection and control unwanted vibration.

Where the designer feels he doesn't know enough, he orders tests to learn more. Where he makes a decision based on extrapolation of previous experience or traditional analysis, he orders a test to verify that the analysis is accurate. When he is satisfied that the design will meet the performance requirements, he releases it to production.

After the release of the drawings for production, testing is used to determine that the output of the production line stays within the limits prescribed by the designer. Tests are performed to assure that no gross deviations from specifications exist. And tests are performed to verify that the equipment operates within the prescribed limits of performance for a reasonable time.

Neither the engineer responsible for designing a part, nor the project engineer responsible for development of the system nor the customer buying the system can guarantee, with absolute certainty, that the system will work when "the switch is closed". However as tests are run and data become available each of these individuals will qualitatively assess this data and will each reach a subjective decision as to whether or not the probability has been increased that the system will work when the switch is pulled. Contracts have, and will be, cancelled when this assessment of quantitative data is negative. On the other hand, large amounts of money have been authorized and expended when a specific individual - with appropriate authority - has made a positive assessment. As a specific example of the latter, consider the relationship between the success of the nuclear submarine, Nautilus, and the decision to convert the nuclear submarine, George Washington, to a Polaris carrier. The assessment by the designer or project engineer can be a decisive factor in the conduct of a development program. It is, therefore, necessary to provide results of test data in such a form that this qualitative assessment can be made in a reasonable fashion.

One of the principal objectives of a test program is to provide timely quantitative data to the engineer to enable him to make decisions.

1. ASSURANCE

The satisfaction of the judgment of the engineer that the equipment will perform reliably will be called assurance. It will be based on two factors, his qualitative satisfaction that the design is "right" including verification by testing that his analyses were good, and proof (statistical verification) that the output of the production line meets expectation.

1.1 QUALITATIVE ASSURANCE

Part of the evidence used by a designer to satisfy himself that a design will be adequate, is the similarity of the design to existing successful equipment. Part comes from his knowledge that the analysis has been thorough, taking all important factors into account. This evidence, when backed up by tests that prove to him that his assumptions are substantiated, is all he needs to give him assurance that the design is satisfactory

The customer, when the design is contracted, needs a means to evaluate this evidence. He would prefer not to be faced with major design modifications after the equipment is built and delivered. He would usually prefer that the delivery not be delayed by major correction of deficiencies discovered during acceptance testing. To obtain assurance of this type (that analyses were thorough and competent and were supported by test results) requires that the customer somehow obtain visibility of the analyses and decisions of the designer as well as the results of all tests conducted. This, in recent contracting, is done through such devices as reliability predictions, design reviews, failure diagnosis requirements in the contract. The reports generated by such activities provides the customer with objective evidence that the designer did a competent job. Equivalent evidence can be obtained that the production and assembly areas are competently controlled through enforced requirements for inspection. The evidence (data) furnished as the result of testing, is invariably statistical in nature. No two tests ever yield exactly the same data. The random variations in test conditions provide the variability of data mentioned in our last chapter. Test conditions may include a "bias". The test of every possible combination of parameters, to eliminate a bias, turns out to require very extensive testing. Statistical design of experiments permits the statistician to improve the efficiency of testing, providing a test program that yields the most pertinent information for the least cost. This is a specialized area and always should be performed by (or rather with the assistance of) specialists in the field of statistics. And like any design, must be done before the tests are run.

1.2 QUANTITATIVE ASSESSMENT

It sometimes happens that an engineer who is "positive" that his answer is right turns out to be wrong. Qualitative judgment can never be relied on entirely. If a system could be operated for an extremely long time, the true reliability could be "measured" Lacking such extreme time of operation, the engineer would like to place a limit or bound on what he can say about the system. Treating the data for a particular test as a "random" sample of data from the population we might discuss what the "statistical" meaning of the data is.

2. APPLICATION OF STATISTICAL THEORY

The interpretation of data derived in a test plan depends, of course, on the purpose for which the testing was performed, the care with which the tests were conducted and documented and the adequacy of the plan to provide the information desired. When the purpose of the testing is to develop quantitative assurance that a required reliability has been achieved, the quantitative measure of this assurance is termed confidence.

2.1 BASIC ASSUMPTIONS

On developing equipment we start with the assumption that every part will act in a definable way, that every equipment produced will be exactly alike , exactly like the blueprints. Every time we conduct a particular test, we should get exactly the same result. But we know equipment does not come out identical. Each equipment will be different, having variations from the basic design. If an infinite number of these equipments were built the minor variations of each parameter would form some pattern. But we cannot determine what this pattern is from testing one unit. We cannot, usually, test all the units built, particularly when the test results in destruction. We wouldn't have any to use. As the nuclear engineers have done in a similar situation we turn to the field of statistics, making the following assumptions.

(a) The true reliability of the equipment is a specific number, not determinable.

(b) Certain of the equipments will fail on test; others succeed. The probability that an equipment will succeed is a measure of the true reliability of the system.

(c) The equipments tested are a sample drawn from a conceptual infinite number of equipments all built to the design.

2 FORM OF THE STATEMENT

The numerical reliability statement we make about the equipment as a result of testing is made in two forms: (a) Point estimate, and (b) Interval estimate.

3. RELIABILITY ESTIMATION

3.1 POINT ESTIMATES

A point estimate is a number which is an estimate of the true value of a parameter and is based on an available sample of observed data. The point estimate of reliability for example is usually just the ratio of the number of successes to the number of trials. The point estimate of mean life may be computed as follows:

Suppose that we have conducted tests to failure of a number of essentially identical components and have recorded the times to failure, $t_1, t_2 \ldots t_n$ for each failed component. The point estimate of mean life is the sum of the times to failure, divided by the number of failures, in this case

$$\text{Mean Life} = \frac{\sum_{i=1}^{n} t_i}{n} \qquad 11.1$$

3.2 POINT ESTIMATION - SYSTEMS

Point estimates of reliability or mean life can be made for any level of assembly, from part to complete systems. Suppose we have a system (or subsystem) made up of three components.

Component A is connected in series with the parallel arrangement of components B and C. Substituting the component point estimate reliabilities on A, B, and C into the following equation yields the point estimate of the system reliability R_S. (Reference Chapter 4 for combinations of probabilities).

$$R_S = R_A(R_B + R_C - R_B R_C)$$

It should be mentioned that use of the foregoing equation implies independence between the constituent components. That is, there is no interaction in the sense that when the components are put together in the system an environment is not created which significantly affects the reliability of any component.

3.3 INTERVAL ESTIMATION

3.3.1 Confidence: Interval estimation involves the construction of a confidence interval on the parameter of interest, e g., reliability or MTBF. A confidence interval is an interval which covers the true but unknown value of the parameter with a given degree of confidence. The construction of the interval is based on test information and certain assumptions with regard to the underlying distribution. How the interval is actually established will be discussed a bit later in this section. At this point, we attempt to provide some insight into the confidence interval concept.

"A servo-amplifier has a 1000 hour reliability of 97% at the 90% confidence level." What do these words mean? The reliability portion of the statement says: "There is a 97% probability that the servo-amplifier will function satisfactorily, under specified conditions, for a period of 1000 hours." The second part adds: "There is a 90% chance that the reliability of the servo-amplifier is at least as good as we have just stated."

Many people find this puzzling. Why make a statement about some percentage of probability, then almost in the same breath admit that we are not altogether certain? Couldn't we wrap up the percentages in a single figure?

To answer this question, consider first the case of a man reaching blindfolded into a bucket to pull out a marble. He knows that the bucket contains 500 marbles, 200 black ones and 300 white ones. We'll say that he counted the marbles himself, put them into the bucket, and stirred them around to assure random selection. The man can now say with perfect confidence, "There is a 40% probability that a marble withdrawn at random will be a black one." No confidence level needs to be added; the statement just made is known to be 100% true.

Now suppose that the man dips into another bucket, this one containing a very large number of marbles of some unknown assortment. We permit him to withdraw 10 marbles at random, then look at them to obtain some idea as to what may be the composition of the mixture in the bucket. Suppose that, in the sample of

10, he observes 3 black marbles, 6 white ones, and one red one. He might then say, "There is a 30% probability that a marble withdrawn at random from this bucket will be black." But this statement cannot be made with complete assurance that it is correct, for the man doesn't know what's in the bucket; he can only make an educated guess based on the limited amount of information obtained from the sample. So he has to add a statement that will indicate whether he's in a position to make a pretty accurate estimate or is only guessing.

So it is with statements concerning reliability. If we life-tested all servo-amplifiers of certain Mark and Model number, we would have a complete knowledge of the failure pattern for this particular device. We could then issue, without qualification, a statement of what chance a single newly manufactured unit would have of working properly for 1000 hours. But nobody is going to destroy an entire output for the sake of perfect information. Rather, we test a few, in the same fashion as the fellow reaching into the bucket for 10 marbles, and make an educated guess about the characteristics of a product from which our particular sample was drawn. Then, to be completely honest, we own up that our prediction is based on sample information without knowledge of the population, and attach a "percent confidence level," so that all may know what test data we had to support our estimate.

Naturally, the more units we test, the better can be our guess and the higher the confidence we can have in it. (This corresponds to the blindfolded man being given the opportunity to examine 20 or 50 marbles from the bucket of unknown composition, instead of only 10 as mentioned previously.) Finally, the more modest is our reliability claim the higher can be our confidence that the reliability is at least as high as we are claiming.

The foregoing discussion points up the fact that we can only make statements about a probability or reliability with perfect assurance or confidence when the sample observed is the complete population. Obviously, there is an intimate relation between confidence and probability. This relation is indicated in the accompanying Figure 11-9. The numerical values in the table are computed by techniques to be explained presently. One would guess that, based on a sample of 10, the estimate of 30% for the probability of drawing a black is not very good. As a matter of fact, it turns out that we are only 38.3% confident that the true probability is greater than 30%. On the other hand, if we had observed 12 black marbles in a sample of 40, we could be 44.1% confident that the true probability is greater than 30%. This

PROBABILITY VS. CONFIDENCE

SAMPLE SIZE: 10

RESULT: 3 BLACKS

PROBABILITY	CONFIDENCE
0	1
0.1	0.930
0.2	0.678
0.3	0.383
0.4	0.167
0.5	0.055
0.6	0.012
0.7	0.002
0.8	--
0.9	--
1	--

result corresponds to intuition; it is a consequence of the greater amount of data in the second sample. Returning to the sample of 10 with 3 blacks observed, we would find that the confidence in a lower probability, say 20%, is 67.8%. When we make some inference about probability (or reliability) from observed results, there is some associated confidence. There is a need, then, for assessing quantitatively our degree of confidence in such an inference.

So far the confidence concept has been discussed in a general sort of way, and some numerical results have been given. How are these results obtained, and what precisely is the meaning of a confidence interval?

3.3.2 Binomial Distribution: First let us consider the binomial case. Suppose we have performed n independent trials and s of them were successful according to some defined criterion. (In the marble example n = 10 and s = 3.) Designate p_L as the lower bound at confidence level α; by lower bound here we simply mean the probability value which corresponds to confidence level α. Using p_L as the basic probability in the binomial probability expression, form the probability of obtaining a result at least as good as the actual observed one, and set this equal to one minus confidence. In mathematical notation,

$$\sum_{i=1}^{n} \binom{n}{i} p_L^i (1 - p_L)^{n-i} = 1 - \alpha \qquad 11.2$$

For a given value of α this equation can be solved for p_L. Or for a given value of p_L the confidence α can be determined.

Having obtained p_L for some particular α, we now make the statement that

$$P(p_L \leq p) = \alpha$$

which is read as: "The probability that the computed lower bound is less than or equal to the true (but unknown) probability is α." Perhaps a better way to state it, is: "The probability (confidence) is α that the interval p_L to 1 includes the true probability." Now what does this mean? A computed interval $(p_L, 1)$ either covers the true probability, or it doesn't cover it. How does this jibe with our confidence statement above?

To return to the marble example, suppose we randomly draw repeated (theoretically an infinite number of) samples of size 10 each. The number of blacks, of course, will in general vary from sample to sample. (Previously, we had 3 blacks in such a sample.) At some fixed confidence level, say $\alpha = 0.678$, we compute the lower confidence bound for each sample and consider the set of α - confidence intervals $(p_L, 1)$ thus obtained. It will turn out that 67.8% of the intervals will cover the true probability and 32.2% of them will not.

Now we actually have only one sample of size 10 wherein 3 black marbles were observed and $p_L = 0.2$ for $\alpha = 0.678$. If we make the claim that the interval (0.2,1) contains the true probability, we are either right or wrong. However, since this interval is one of many possible intervals, 67.8% of which cover the true probability, our particular claim has a 67.8% chance of being correct. It is only in the sense of the percentage of correct claims that we say:

$$P(0.20 \leq p) = 0.678$$

Solutions to equation 11.2 can be found in the tables of the binomial probability distribution (1).

In the above description of the meaning of "confidence interval", it can be seen that the frequency interpretation of probability is used; in particular, on <u>repeated</u> sampling from the same density function, a given proportion of such intervals will cover the true parameter value. Unfortunately, the situation wherein there is repeated sampling is the exception rather than the rule. Most frequently, we have one sample and have to base our confidence statement on that one sample's data.

The type of confidence interval obtained from equation 11.2 or from the reliability/confidence charts Figures 11-29 to 11-34 is a one-sided interval. It is called one-sided, because the upper end of the interval is always unity. There is also such a thing as a two-sided interval, whose upper limit, as well as the lower limit, is variable from sample to sample. The confidence concept of a two-sided interval is exactly the same as that of the one-sided, except in this case we are saying that the confidence is the probability that the interval -- lower bound to upper bound (where the upper bound is less than 1.0) -- contains the true value. Our discussion will be limited to the one-sided interval because in reliability applications we are usually concerned more that the reliability exceeds a certain minimum than that it will be found within an interval.

Let us consider briefly a simple application of binomial confidence intervals. Suppose in a particular missile program 20 shots have been fired with 2 failures. We assume here a binomial situation, obviously an over-simplified assumption. The missile reliability cannot be expected to be the same for each shot. Nor would shots be independent of one another, since fixes and improvements are constantly made in the program as a consequence of firing data. Recognizing these limitations, we still assume binomial and make use of the chart on Figure 11-31. This figure provides a graphical solution to equation 11.2 for the case of two failures in any number of tests. Finding 20 trials along the bottom, follow the line up to the 95% confidence curve (the top curve). The intersection falls between .71 and .72 (actually .716). This gives us a 0.716 lower bound reliability at the 0.95 confidence level. At the conclusion of the program the results are 5 failures in 50 launches, giving the same point estimate reliability of 0.9. Superficially there has been no improvement. However, using the chart on Figure 11-34, since we now have 5 failures in 50 tests, we now find that the indicated reliability is about .80 (actually .798) so we can claim a reliability at least as good as 0.798 at 0.95 confidence. Our improved reliability claim is, of course, a consequence of the larger sample size. If the program reliability specification was 0.75 at 95% confidence, it was not met after 20 shots. It was met after 50. The point we make here is simply that attainment of a reliability/confidence specification depends upon, among other things, the number of tests specified in a program and conversely, our requirement for confidence determines the number of tests required. Therefore, such specifications should be imposed on a program only after careful deliberation and compromises between the specifications and program testing costs.

3.3.3 Exponential Distribution: The interpretation of confidence intervals in terms of percentage of correctness of claims is valid regardless of the underlying distribution. What does depend upon the distribution is the technique of computing the interval. So far we have talked in terms of the binomial assumptions, one of considerable importance in reliability practice. Another important distribution, as pointed out in chapters 4 and 5 is the negative exponential distribution of time-to-failure corresponding to the underlying condition of constant failure rate. We now consider the technique for computing a one-sided confidence interval for this case.

The formula for reliability, it will be recalled, is

$$R = e^{-\lambda t}$$

where λ is the underlying constant failure rate and t is the mission or operating time.

Since in a practical situation the amount of test data is finite, we cannot determine λ precisely. We are once again confronted with the need to make some claim about a value at some confidence level. Epstein and Sobel (2) have shown essentially that the upper confidence bound on λ at confidence α is given by

$$\lambda = \frac{\chi^2\ (\alpha,\ 2r + 2)}{2T} \qquad 11.3$$

where r is the number of failures experienced in a test terminated at a prespecified total accumulated time T. The 2r + 2 in formula 11.3 refers to the degrees of freedom of the χ^2 (chi-square) variable. If the test was specified to terminate upon the rth failure, then 2r degrees of freedom should be used.

At this point a few words about the chi-square tables may be appropriate. The chi-square tables give the value of a distribution quite useful in statistics (Figure 11-14) one of their main uses being the determination of confidence limits applicable to the negative exponential distribution. The degrees of freedom determines the shape of the distribution. Its only interest to us is its use as a parameter to determine which of the distributions fits the data we have available. A tabulation of χ^2 for degrees of freedom from 1 to 30 is given in Figure 11-28. The entries in this table are those values, χ_o^2 for which the left-hand area under the curve is equal to α. In our application

$$\alpha = \int_0^{\chi_o^2} f(\chi^2)\ d\chi^2 \qquad 11.4$$

where $f(\chi^2)$ represents the χ^2 density function and $\int_0^{\infty} f(\chi^2)d\chi^2 = 1$.

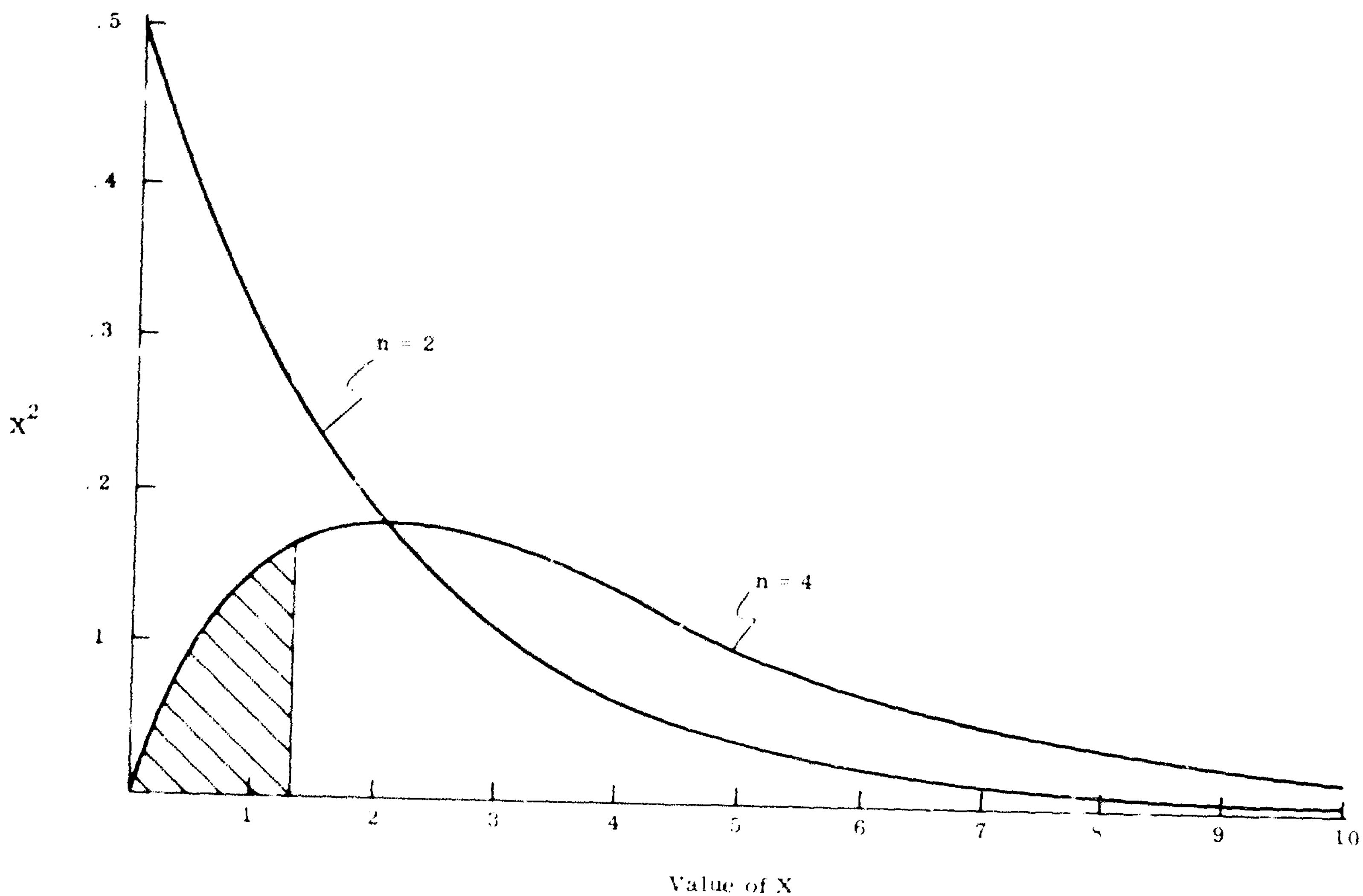
Based on equation 11.4 one may make the confidence statement which reads:

$$P(\lambda_U \geq \lambda) = \alpha \qquad 11.5$$

For a numerical example let us return to the servo-amplifier mentioned at the beginning of this discussion on interval estimation. Let us assume that either one servo was tested to 75,500 hours or that 100 identical specimens were tested, each to 755 hours, and that no failures occurred.

The information and data are summarized as follows:

CHI SQUARE FUNCTION



Mission time, t - 1000 hours
Total test time, T - 75,500 hours
Failures, r = o; degrees of freedom = 2r + 2 = 2
Confidence, γ = 0.90

Applying formula 11.3, as follows $\lambda = \chi^2/2T$. For two degrees of freedom and γ = .90 the value given for χ^2 is 4.61 so

$$\lambda_U = \frac{4.61}{2 \times 75,500} = .0305$$

We find that at the 90% confidence level the upper bound on failure rate is λ_U = 0.0305 failure per thousand hours. The corresponding 90% lower bound on MTBF is $\theta_L = 1/\lambda_U$ = 32,790 hours, which means that we are 90% confident that our servo has an MTBF of 32,790 hours or more. For the 1000 hour mission or operating time the 90% lower confidence bound on reliability is $R_L = e^{-0.0305}$ = 0.970, which of course, is the figure cited earlier. This result means that we may make the claim, with 90% assurance, that the probability of successful servo operation for 1000 hour period is 0.97 or better.

The servo-amplifier example above was worked out by direct computations from the pertinent formulas under the negative exponential assumption. It is possible to obtain essentially the same answers by use of the reliability test demonstration chart, Figure 11-29. This follows because, although the charts were derived under the binomial assumption, they approximate the negative exponential case very well in the regions where n >> r, i.e., where the number of test cycles is much larger than the number of failures. The r for use in the charts is interpreted as the number of mission cycles tested, i.e., n = T/t. In our servo problem n = 75.5 >> 0. Having used the appropriate chart to obtain R_L at some confidence γ, we can compute the corresponding MTBF and failure rate bounds by $\theta_L = -t/\ln R_L$ and $\lambda_U = 1/\theta_L = \ln R_L/t$. The student may verify for himself that this procedure gives essentially the same answers as those computed by the chi square formula.

If one desires to demonstrate a specified reliability at a stated confidence it is obvious that the testing requirements can be established. Figure 11-29 through 11-34, for example, can be used for this purpose. The requirements would be in terms of a given number of failures in a required number of test cycles. If the requirements are met in actual testing, then the reliability/confidence requirement has been met.

Examination of Figure 11-29 to 11-34 will show that as reliability requirements increase, tests required to demonstrate that the reliability has been achieved at a stated confidence increase proportionately. An order of magnitude increase from .9 to .99 say requires an order of magnitude increase in testing from 22 to 235. This is shown in figure 11-17

This indicates that reliability testing to reasonably high confidences may cost excessively, both in terms of test cycles and/or time required, number of specimens, and money.

3.3.4 Summary: The use of testing to develop the statistical level of confidence that the design has achieved a high level of reliability is limited by the amount of money and time the customer can afford. The need for a chosen level of high confidence depends on what other proof is available that will give the designee and customer "reasonable" assurance of high reliability. As discussed earlier, qualitative assurance supports the quantitative assurance (confidence) derived from a successfully completed demonstration plan. It should not supplant it. The degree of support offered by qualitative assurance must be evaluated, on the basis of the evidence shown, by the customer. Based on the total evidence -- his satisfaction that the designer has been complete and competent in his analysis, that the inspection on the production line is adequate, that the testing supports the analysis and the demonstration tests yields a reasonable confidence though not able to be specified quantitatively that the achieved reliability has been met -- the customer can accept the product. Since the evidence cannot be submitted until the acts are performed, the customer must make the initial presumption that the various factors of proof required will be favorable, deciding before negotiating the contract just what evidence he is willing to accept to convince himself, and how much he is willing to pay for, then negotiate the contract and administer it to be sure he gets the quality of design and production desired.

4. DEMONSTRATION TESTING

As pointed out earlier, qualitative assurance should support the demonstration plan, not eliminate it. We recognize that we need an acceptance test plan to decide whether or not a requirement has been met. The purpose of this section is to explain how to develop a test plan or how to understand a test plan proposed by a contractor.

It is generally recognized that a correct decision as to whether or not to accept could be effectively guaranteed if a sufficient

RELIABILITY VS. NUMBER OF TESTS

AT 90% CONFIDENCE

R_L	TESTS REQUIRED, n: $r = 0$	$r = 1$
0.90	22	38
0.99	235	390
0.999	2,300	3,900
0.9999	22,000	39,000

amount of testing were done. Usually, schedule and budgetary limitations do not permit. We are then forced to make this decision with a limited amount of testing, i.e., on a sample the natural inference is that a correct decision cannot be 100% guaranteed. This implies that the contractor is taking some risk that equipment meeting or exceeding the specification will be rejected. The customer, on the other hand, is taking some risk that he will be accepting sub-standard equipment. Statistics gives both parties the capability of numerically assessing the magnitude of these risks as well as determining required changes to the test plan should be magnitude of these risks prove undesirable to either or both of the parties.

4.1 TESTING STATISTICAL HYPOTHESIS

The producer wants to be reasonably sure that equipment meeting the requirements is accepted. He wants to keep his risk to as small a value as possible. He would like to keep the "producer's risk" defined as the probability that an equipment meeting the requirements is rejected, to a numerically small fraction. The customer similarly wants to keep the "consumers risk", defined as the probability that an equipment not meeting the minimum acceptable requirement is accepted, to a numerically small fraction. We thus need a numerical assessment of the magnitude of these risks.

4.2 BASIS OF TEST PROCEDURES

The establishment of a numerical value to the magnitude of the risks involves the extent of testing. Consider for example:

An engineer has two theories to explain a phenomenon. In theory 1 the probability that the phenomenon will occur on any trial is 50%. Under theory 2 the probability is only 31%. He would like to learn which theory is correct. To find out, he decides to conduct an experiment 10 times and record whether or not the phenomenon occurs. In attempting to interpret the result of the experiment as to which theory to prefer he feels that the decision should involve the relative probabilities of observing this result when $p = .50$ and when $p = .31$. Setting up the hypothesis that $p = .50$ as what is usually called the null hypothesis, H_0, he can test this against the alternate hypothesis, H_1, that $p = .31$. Using a tabular form, Figure 11-19 he computes the probability of observing each of the possible outcomes on each hypothesis.

Since the events are not time dependent, but rather independent trials, the binomial equation will be used.

PROBABILITY OF POSSIBLE OUTCOMES

(1) Number of Successes k	(2) $\binom{10}{k} (1/2)^k (1/2)^{10-k} =$	(3) $\binom{10}{k} (.31)^k (.69)^{10-k} =$	(4) $\frac{\text{Column (2)}}{\text{Column (3)}}$
10	.0009766	.0000082	119
9	.0097656	.0001824	54
8	.0439453	.0018273	24
7	.1171875	.0108458	11
6	.2050781	.0422460	5
5	.2460937	.1128378	2
4	.2050781	.2092958	0.98
3	.1171875	.2662012	0.44
2	.0439453	.2221921	0.20
1	.0097656	.1099015	0.09
0	.0009766	.0244619	0.04

In this table he notes that 10 successes is 119 times more likely under the hypothesis p = 1/2 than it is under the hypothesis p = .31. If 10 successes occur, therefore, the hypothesis p = 1/2, is to be preferred. In a similar way 0 successes is (1/25th) as likely under p = 1/2 than under p = 0.31. If no successes occur, the hypothesis, p = .31, is preferred. It is intuitively clear to this engineer that his decision should be based on a ratio of probabilities under the two hypotheses of the observed result. However, the observance of a particular result, even though highly favorable to one hypothesis, does not negate the possibility that the other hypothesis is true. Therefore, if this engineer is to reach some conclusion and then to take action on the basis of this conclusion, he must be willing to accept some risk of reaching an erroneous conclusion.

Obviously he will reject the hypothesis p = .50 and prefer p = .31 if two or less trials result in success, this gives him 5:1 odds of being right. If p = .50 is actually the correct solution, the probability of achieving 0, 1 or 2 successes is the sum of the probabilities for these numbers of successes (Figure 11-20) or about .055. This is the risk he takes of being wrong, of coming to an erroneous conclusion based on the tests. This risk is usually called the producers risk, the probability that an observation will fall into a region of rejection when the hypothesis is in fact true.

Alternately, if p is in fact .31 the probability that he will observe the result, 0, 1 or 2 successes, is .356, leaving a probability of .644 that some other result will be obtained (3 or more successes). This value .644 is the probability that he will accept the hypothesis p = .50 when p is in fact .31. This is the consumers risk, the probability of incorrectly accepting the null hypothesis when the alternate hypothesis is true.

Figure 11-20 shows that this engineer does have the capability of controlling the magnitude of the risk by appropriate selection of the critical region.

Of course, the engineer still has a remaining decision -- that of whether or not the risks are acceptable. If he does find a region of rejection, e.g., 0 or 1 or 2 successes that has acceptable values of producers and consumers risks the derivation of the test procedure is complete.

His choice of decision criteria (two or less occurrences in ten trials) still leaves him a risk of 64% that he will incorectly accept the hypothesis p = .5. Changing the acceptance region to

CONTROLLING MAGNITUDE OF RISKS

Testing H_0 : $p = 1/2$ against alternative H_1 : $p = 0.31$ 10 Trials

NUMBER OF SUCCESSES DEFINING REJECTION REGION	PRODUCERS RISK (Reject H_o when true)	CONSUMERS RISK (Accept H_o when false)
0 successes	0.001	1 - 0.024 = .976
0 successes <u>or</u> 1 success	0.011	1 - 0.134 = .866
0 <u>or</u> 1 <u>or</u> 2 successes	0.055	1 - 0.356 = .644

0, 1, 2 or 3 occurrences, reduces his (the consumer's) risk to 38% but increases the producers risk to 17%.

If the engineer cannot find a region of acceptance that provides acceptable values of the risks, he must consider the use of more than 10 trials.

4.3 FORMAL TEST PROCEDURES

Using the concept just introduced we can develop a formal test procedure to determine the rejection region for a reliability demonstration test.

A new system is assumed to have a negative exponential density function for times to failure. The required reliability is 425 hours MTBF. A test is to be designed to test this value (425 hrs. MTBF) against an alternate hypothesis of 250 hrs. MTBF. (considered a minimum acceptable reliability)

$$H_0 = 425 \text{ hrs}$$

$$H_1 = 250 \text{ hrs}$$

to determine the form of the region in which the null hypothesis will be rejected, we compute the ratio of probabilities of the observed result under the two hypothesis, establishing the rejection region such that if the ratio P_0/P_1 is less than some value, the null hypothesis will be rejected. A number, T, representing the length of time the test is to be run, is computed such that, if the equipment fails within the test time, the hypothesis is to be rejected. To determine the value of T, assume H_0 is true. Select a value for the producers risk.

The producers risk is the probability that a failure will occur prior to the end of the test (time = T) when the MTBF is equal to or greater than 425 hrs. For this example, we will select a value of 0.10 for the producers risk.

As you will recall from our discussion of confidence, the probability that an interval contains the true value of MTBF was expressed by the equation

$$\lambda = \frac{1}{\theta} = \frac{\chi^2}{2T}$$

Solving for our test time, T we find

$$T = \frac{\chi^2 \cdot \theta}{2} \qquad 11.5$$

Using 2 degrees of freedom, since the test is specified to terminate on the first failure, and .10 probability that the interval contains the true value we find

$$\chi^2 = .211$$

$$T = \frac{.211 \times 425}{2} = 44.6 \text{ hours}$$

The test procedure is to put the system on test for 44.6 hours. If it fails before this time H_0 is rejected. If it does not fail the system is accepted.

The consumers risk is computed as the probability that the system does not fail prior to 44.6 hours when the MTBF is really 250 hours

$$p(s) = e^{-44.6/250} = e^{-.18} = .835$$

This means that the test procedure will accept systems with an MTBF of 250 hours 83.5% of the time.

Systems with MTBF lower than 250 hours (considered unacceptable) will be accepted with gradually reducing probabilities. The MTBF of 250 hours is a limiting condition defining the consumers risk as a probability approaching 83.5% that bad systems, systems with MTBFs lower than 250 hours will be accepted.

4.4 SEQUENTIAL TEST PLANS

This value of the consumers risk is considered unacceptable. One procedure, used in industry is to superimpose a second test procedure on top of the first one. In this second test procedure the null hypothesis (H_0') is the minimum acceptable value of MTBF (250 hrs). This value is to be tested against a (new) alternate hypothesis, H_1' of 425 hours. A test time is to be computed such that a system with MTBFs equal to or less than 250 hours will not be accepted more than 10% of the time. (note the reversal of null and alternate hypotheses.)

Entering a table of χ^2 with 2 degrees of freedom and the probability of .90, since this time we want a probability of 90% that the true MTBF is greater than 250 hours (10% risk that it is not). The value of χ^2 is found to be 4.61

$$T = \frac{\chi^2 \theta}{2} = \frac{4.61 \times 250}{2} = 575.6 \text{ hours}$$

The system is placed on test. If it fails prior to the 44.6 hours it is rejected. If it operates successfully for 575.6 hours it is accepted. If a failure occurs between 44.6 and 575.6 hours, the trial is continued. We are now concerned about a second failure. To compute the times to the second failure, select values from the χ^2 table for the same risks as before but with 4 degrees of freedom (2 failures).

$H_0 = 425$ $\qquad\qquad$ $H_0' = 250$

$\chi^2(.10,4) = 1.06$ $\qquad\qquad$ $\chi_2(.90,4) = 7.78$

$T_2 = 225$ $\qquad\qquad$ $T_2^1 = 970$

If the second failure occurs prior to 225 hours the system is rejected. If the second failure has not occurred by 970 hours, the system is accepted. Again should the second failure occur in the interval 225 to 970 hours, no decision is reached. The procedure is repeated, computing the times for three failures, and so on. A more detailed discussion of the sequential test plans will be found in chapter 10.

The test plan just described has established the risks of "good" (MTBF >425 hours) systems being rejected and "bad systems (MTBF < 250 hours) accepted at ten percent. Suppose, however we redefine a bad system as one having an MTBF less than 400 hours. The initial values for the first plan based on H_0 = 425 remains the same, (assuming the risks are to be kept at ten percent). A comparison of this revised plan with the previous one is given in Figure 11-25 .

Test time of 921 hours is required if no failure occurs. If the first failure does occur in the no-decision- range, (44.6, 921) and this is quite likely, then, after repair, the system is continued on test, being accepted if the test runs 1552 hours without a second failure. The Bureau might not wish to buy a "used" computer with an MTBF of 425 hours after being on trial for 1552 hrs. The requirement of testing $\theta = 425$ against $\theta = 400$ at 10% risks is not a reasonable requirement in that the trial times involved are, for all practical purposes, equivalent to destructive testing. To reduce trial time, a "bad" computer may be redefined as $\theta = 250$ and/or the 10% consumers risk may be increased.

It may be noted that if you test H_0: $\theta = 425$ against H_1: $\theta = 400$ at $\alpha = 0.10$, the same rejection region, (0,44.6) is obtained. Indeed, the interval, (0,44.6), is suitable to test $\theta = 425$ against any θ less than 425 as long as $\alpha = 0.10$. In this situation,

SEQUENTIAL TEST PLAN

$H_o = 425$, $H_1 = 400$

(PRODUCERS RISK, CONSUMERS RISK, BOTH 10%)

FAILURES	REJECT IF FAILURE OCCURS BEFORE	ACCEPT IF FAILURE HAS NOT OCCURRED BY	ACCEPT CRITERIA FOR $H'_o = 250$
1	44.6 hours	921 hours	(576 hours)
2	225 hours	1552 hours	(970 hours)
3	467 hours	2120 hours	(1325 hours)
4	731 hours	2680 hours	(1675 hours)
5	1033 hours	3200 hours	(2000 hours)

one has been able to derive one rejection interval to test the simple null hypothesis $\theta = 425$ against the composite alternative, $\theta < 425$. Using this common rejection region, one could compute the consumers risk with this test for say $\theta = 424$, $\theta = 400$, $\theta = 250$ etc., making his choice on the risk he was willing to take.

5. SEQUENTIAL SAMPLING PLANS

5.1 AGREE PLAN

Sequential test plans have been computed and are available for use (3) in the report of the Ad Hoc Group on Reliability of Electronic Equipment (AGREE, Task Group 3). This acceptance table makes the following assumptions:

(a) Both Producers Risk and Consumers Risk are set at 10%:
(b) The alternative hypothesis has been set at 2/3 the value of the null hypothesis.

This second assumption controls the Consumers Risk. In effect it is saying the probability is 10% that an equipment whose MTBF is only 2/3 the specified value will be accepted. If the specified value of MTBF is 1000 hours, the equipment will be accepted with an MTBF lower than 670 hours ten percent of the time.

5.2 ADDITIONAL SOURCES

The AGREE sequential test plan is incorporated as the test plan for Electronics Equipment in MIL R 22732 (SHIPS). MIL STD 105 provides plans for sampling by attributes and may be used as outlined in that chapter for developing test plans, or for interpreting the meaning in terms of risk in plans proposed by contractors.

6. REFERENCES

1. Tables of Binomial Probability Distribution Function, National Bureau of Standards Applied Mathematics Series 6, U. S. Government Printing Office, Washington, D. C.

2. Life Testing, Epstein and Sobel, Journal of the American Statistical Association, Vol. 48, 1953.

3. Reliability of Military Electronic Equipment, Report by Advisory Group on Reliability of Electronic Equipment,

4 June 1957, U. S. Government Printing Office, Washington, D. C.

4. Introduction to the Theory of Statistics, A. F. Mood, McGraw-Hill Book Company, 1950.

5. Mathematical Methods of Statistics, H. Cramer; Princeton University Press.

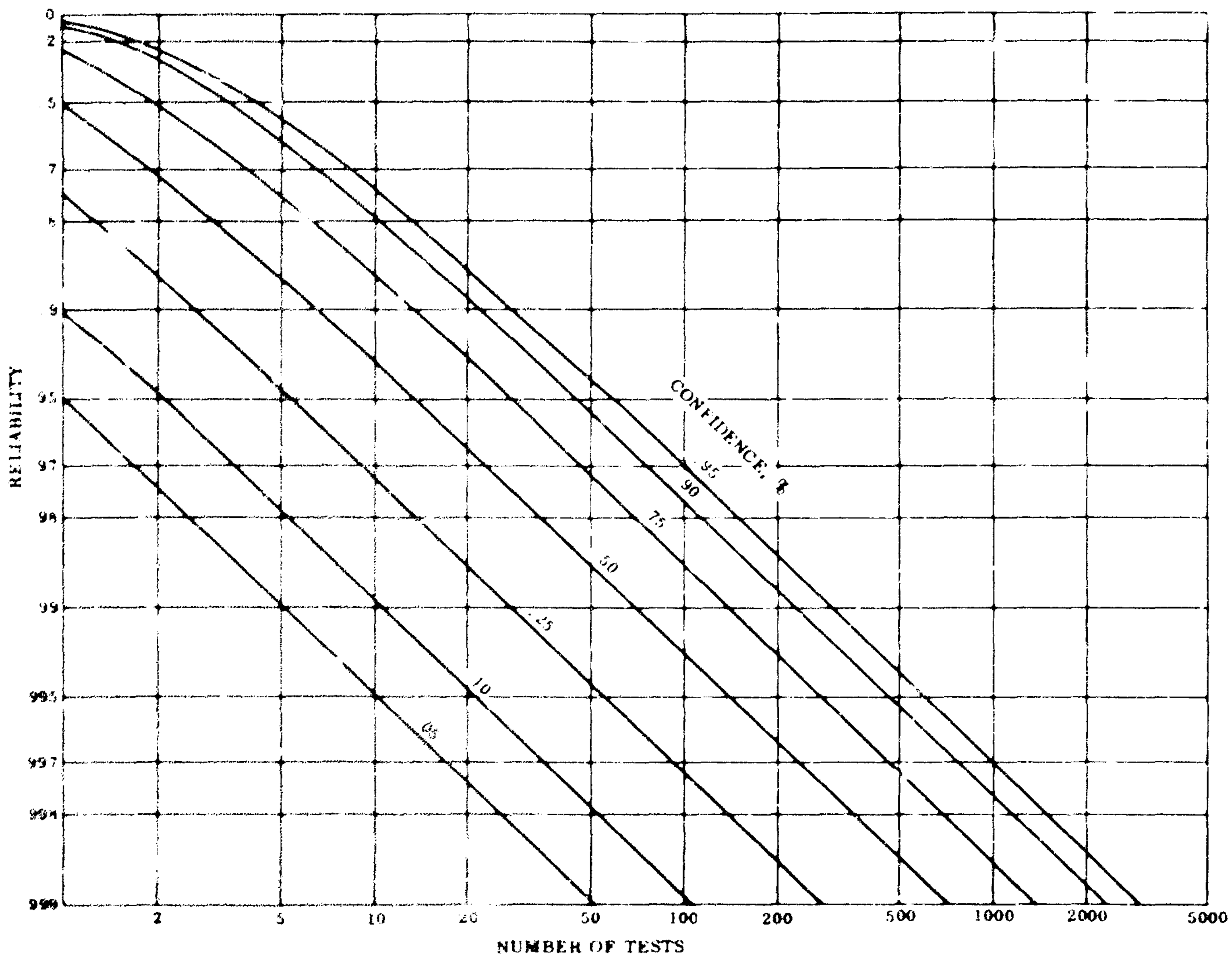
CHI-SQUARE (X^2) DISTRIBUTION TABLE

Probability, %

Degrees of freedom (2r)	0.05	0.1	0.5	1.0	2.5	5.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	95.0	97.5	99.0	99.5	99.9	99.95	Degrees of freedom (2r)
1	$0^{6}393$	$0^{5}157$	$0^{4}393$	$0^{3}157$	$0^{3}982$	$0^{2}393$	.0158	.0642	.148	.275	.455	.708	1.07	1.64	2.71	3.84	5.02	6.63	7.88	10.8	12.1	1
2	$0^{2}100$	$0^{2}200$	.0100	.0201	.0506	.103	.211	.446	.713	1.02	1.39	1.83	2.41	3.22	4.61	5.99	7.38	9.21	10.6	13.8	15.2	2
3	.0153	.0243	.0717	.115	.216	.352	.584	1.00	1.42	1.87	2.37	2.95	3.67	4.64	6.25	7.81	9.35	11.3	12.8	16.3	17.7	3
4	.0639	.0908	.207	.297	.484	.711	1.06	1.65	2.19	2.75	3.36	4.04	4.88	5.99	7.78	9.49	11.1	13.3	14.9	18.[illegible]	20.0	4
5	.158	.210	.412	.554	.831	1.15	1.61	2.34	3.00	3.66	4.35	5.13	6.06	7.29	9.24	11.1	12.8	15.1	16.7	20.5	22.1	5
6	.299	.381	.676	.872	1.24	1.64	2.20	3.07	3.83	4.57	5.35	6.21	7.23	8.56	10.6	12.6	14.4	16.8	18.5	22.5	24.1	6
7	.485	.598	.989	1.24	1.69	2.17	2.83	3.82	4.67	5.49	6.35	7.28	8.38	9.80	12.0	14.1	16.0	18.5	20.3	24.3	26.0	7
8	.710	.857	1.34	1.65	2.18	2.73	3.49	4.59	5.53	6.42	7.34	8.35	9.52	11.0	13.4	15.5	17.5	20.1	22.0	26.1	27.9	8
9	.972	1.15	1.73	2.09	2.70	3.33	4.17	5.38	6.39	7.36	8.34	9.41	10.7	12.2	14.7	16.9	19.0	21.7	23.6	27.9	29.7	9
10	1.26	1.48	2.16	2.56	3.25	3.94	4.87	6.18	7.27	8.30	9.34	10.5	11.8	13.4	16.0	18.3	20.5	23.2	25.2	29.6	31.4	10
11	1.59	1.83	2.60	3.05	3.82	4.57	5.58	6.99	8.15	9.24	10.3	11.5	12.9	14.6	17.3	19.7	21.9	24.7	26.8	31.3	33.1	11
12	1.93	2.21	3.07	3.57	4.40	5.23	6.30	7.81	9.03	10.2	11.3	12.6	14.0	15.8	18.5	21.0	23.3	26.2	28.3	32.9	34.8	12
13	2.31	2.62	3.57	4.11	5.01	5.89	7.04	8.63	9.93	11.[illegible]	12.3	13.6	15.1	17.0	19.8	22.4	24.7	27.7	29.8	34.5	36.5	13
14	2.70	3.04	4.07	4.66	5.63	6.57	7.79	9.47	10.8	12.1	13.3	14.7	16.2	18.2	21.1	23.7	26.1	29.1	31.3	36.1	38.1	14
15	3.11	3.48	4.60	5.23	6.26	7.26	8.55	10.3	11.7	13.0	14.3	15.7	17.3	19.3	22.3	25.0	27.5	30.6	32.8	37.7	39.7	15
16	3.54	3.94	5.14	5.81	6.91	7.96	9.31	11.2	12.6	14.0	15.3	16.8	18.4	20.5	23.5	26.3	28.8	32.0	34.3	39.3	41.3	16
17	3.98	4.42	5.70	6.41	7.56	8.67	10.1	12.0	13.5	14.9	16.3	17.8	19.5	21.6	24.8	27.6	30.2	33.4	35.7	40.8	42.9	17
18	4.44	4.90	6.26	7.01	8.23	9.39	10.9	12.9	14.4	15.9	17.3	18.9	20.6	22.8	26.0	28.9	31.5	34.8	37.2	42.3	44.4	18
19	4.91	5.41	6.84	7.63	8.91	10.1	11.7	13.7	15.4	16.9	18.3	19.9	21.7	23.9	27.2	30.1	32.9	36.2	38.6	43.8	46.0	19
20	5.40	5.92	7.43	8.26	9.59	10.9	12.4	14.6	16.3	17.8	19.3	21.0	22.8	25.0	28.4	31.4	34.2	37.6	40.0	45.3	47.5	20
21	5.90	6.45	8.03	8.90	10.3	11.6	13.2	15.4	17.2	18.8	20.3	22.0	23.9	26.2	29.6	32.7	35.5	38.9	41.4	46.8	49.0	21
22	6.40	6.98	8.64	9.54	11.0	12.3	14.0	16.3	18.1	19.7	21.3	23.0	24.9	27.3	30.8	33.9	36.8	40.3	42.8	48.3	50.5	22
23	6.92	7.53	9.26	10.2	11.7	13.1	14.8	17.2	19.0	20.7	22.3	24.1	26.0	28.4	32.0	35.2	38.1	41.6	44.2	49.7	52.0	23
24	7.45	8.08	9.89	10.9	12.4	13.8	15.7	18.1	19.9	21.7	23.3	25.1	27.1	29.6	33.2	36.4	39.4	43.0	45.6	51.2	53.5	24
25	7.99	8.65	10.5	11.5	13.1	14.6	16.5	18.9	20.9	22.6	24.3	26.1	28.2	30.7	34.4	37.7	40.6	44.3	46.9	52.6	54.9	25
26	8.54	9.22	11.2	12.2	13.8	15.4	17.3	19.8	21.8	23.6	25.3	27.2	29.2	31.8	35.6	38.9	41.9	45.6	48.3	54.1	56.4	26
27	9.09	9.80	11.8	12.9	14.6	16.2	18.1	20.7	22.7	24.5	26.3	28.2	30.3	3219	36.7	40.1	43.2	47.0	49.6	55.5	57.9	27
28	9.66	10.4	12.5	13.6	15.3	16.9	18.9	21.6	23.6	25.5	27.3	29.2	31.4	34.0	37.9	41.3	44.5	48.3	51.0	56.9	59.3	28
29	10.2	11.0	13.1	14.3	16.0	17.7	19.8	22.5	24.6	26.5	28.3	30.3	32.5	35.1	39.1	42.6	45.7	49.6	52.3	58.3	60.7	29
30	10.8	11.6	13.8	15.0	16.8	18.5	20.6	23.4	25.5	27.4	29.3	31.3	33.5	36.3	40.3	43.8	47.0	50.9	53.7	59.7	62.2	30

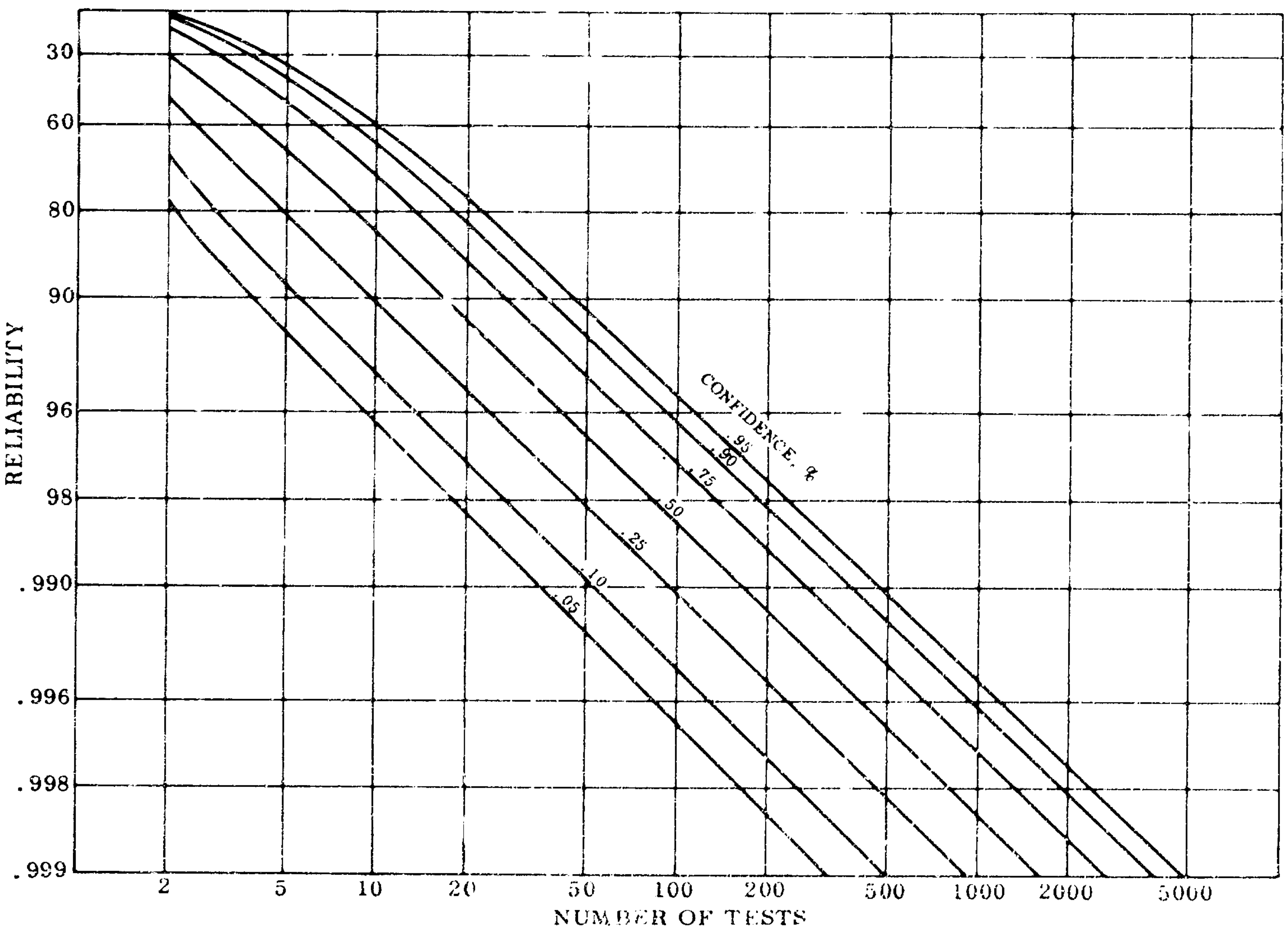
RELIABILITY TEST REQUIREMENTS

ZERO FAILURES



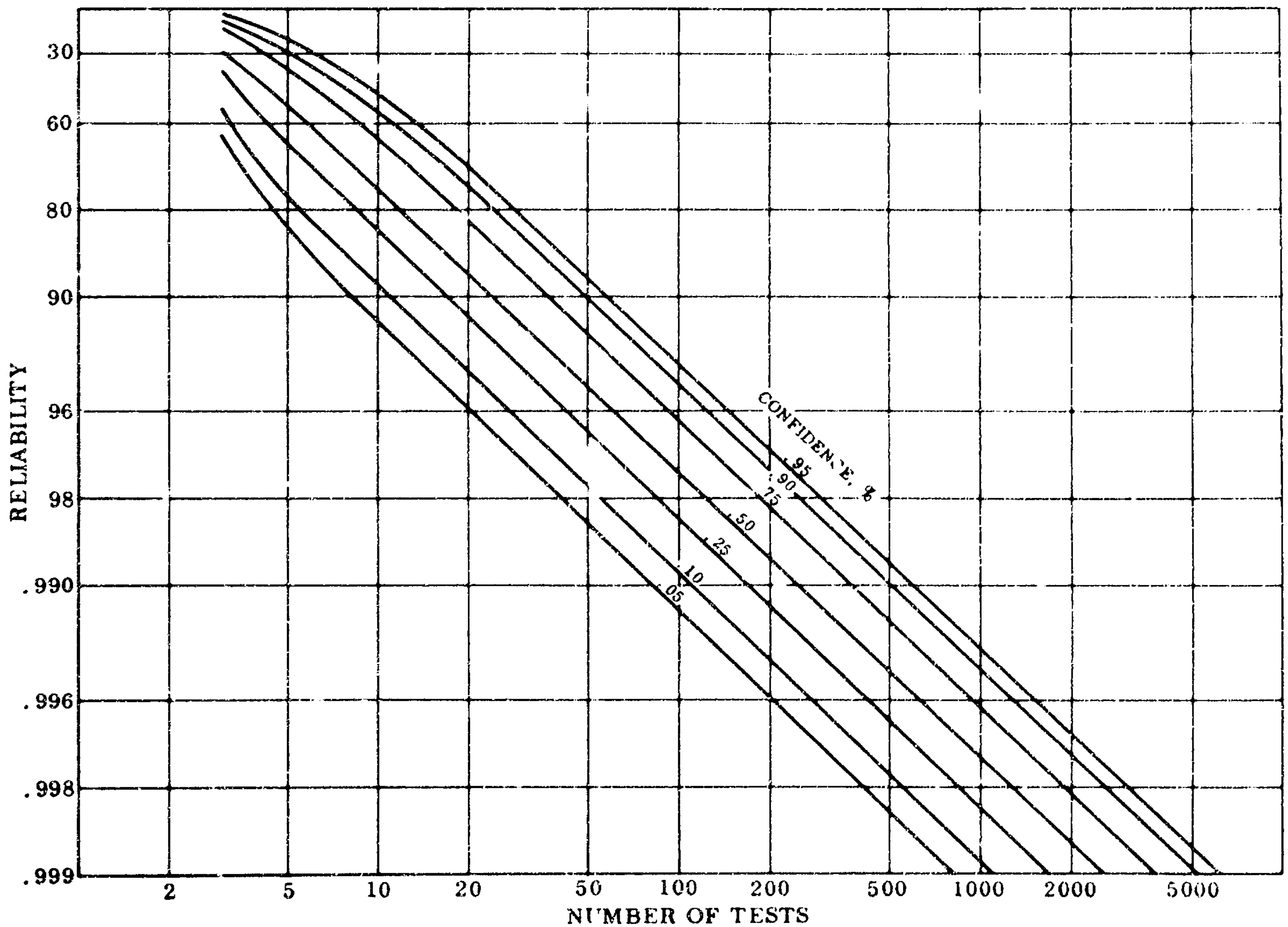
RELIABILITY TEST REQUIREMENTS

ONE FAILURE

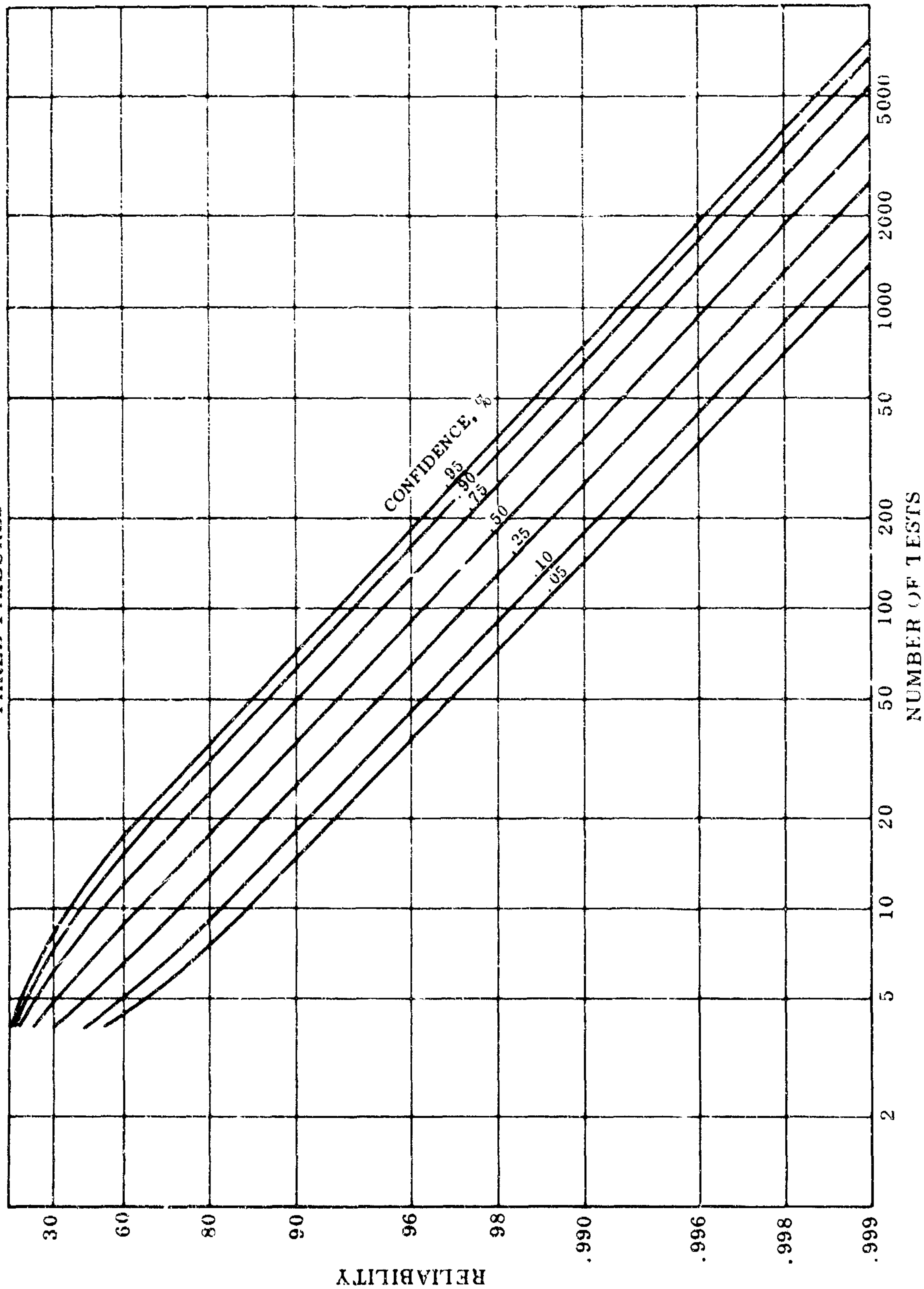


RELIABILITY TEST REQUIREMENTS

TWO FAILURES

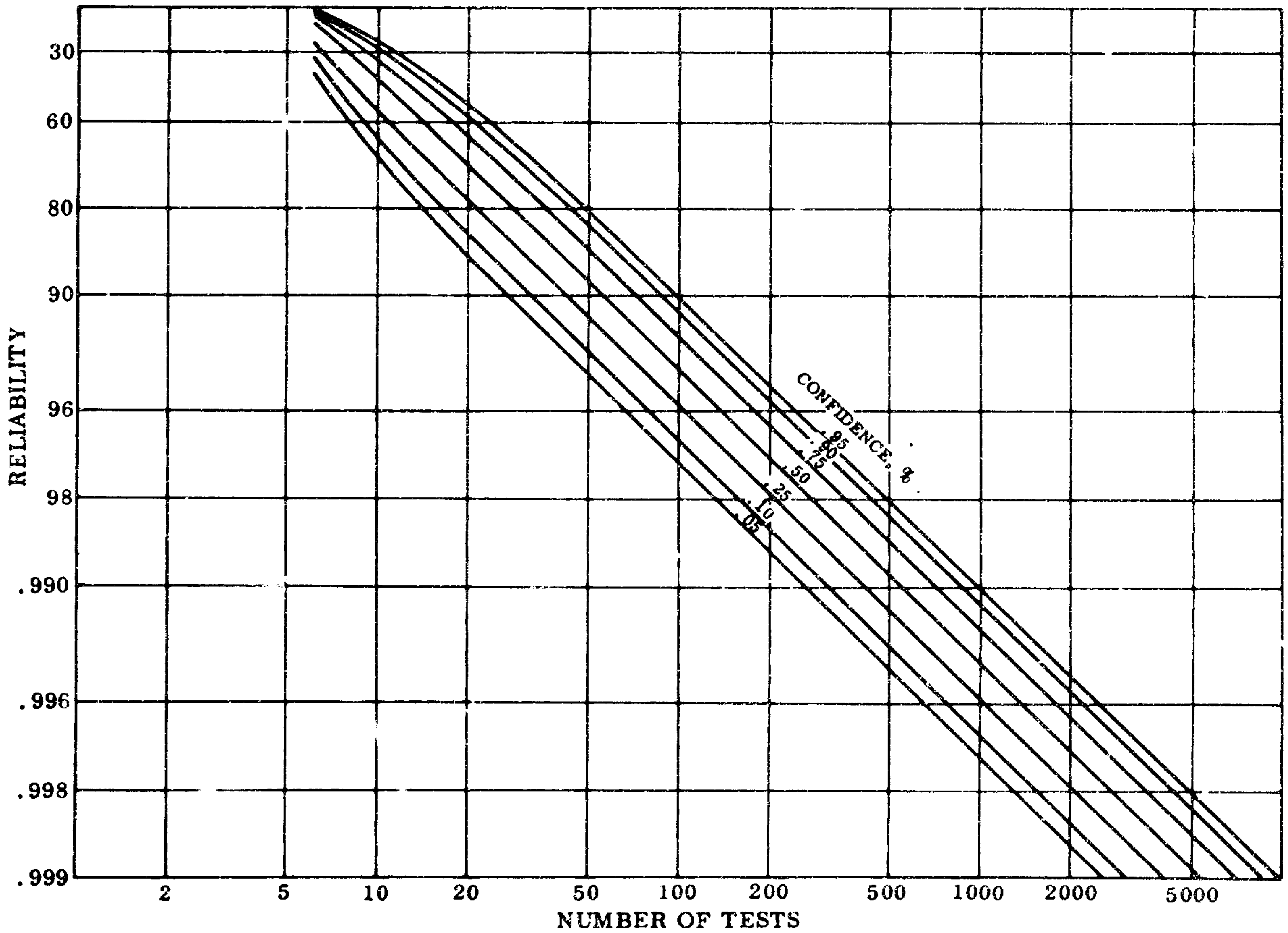


RELIABILITY TEST REQUIREMENTS
THREE FAILURES



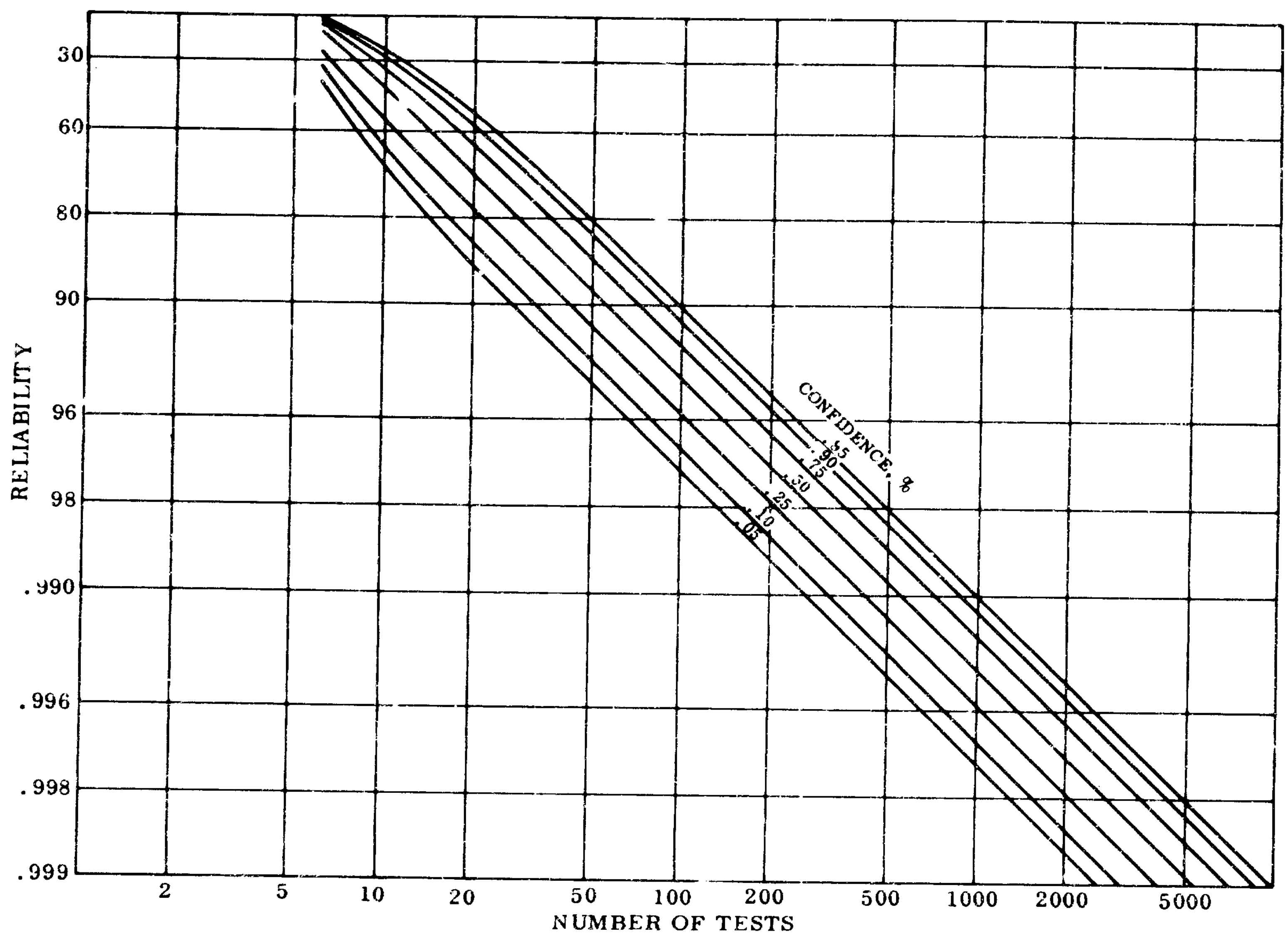
RELIABILITY TEST REQUIREMENTS

FOUR FAILURES



RELIABILITY TEST REQUIREMENTS

FIVE FAILURES



Chapter 12

FAILURE MODES & EFFECTS ANALYSIS

Chapter 12

FAILURE MODES & EFFECTS ANALYSIS

A Failure Modes and Effects analysis is a qualitative means of evaluating the reliability, maintainability and safety of a design by considering potential failures and the resulting effects on a system. Basically the analysis involves the identification and tabulation of the ways (or modes) in which a part, component or system can fail, as for example (1), a ball bearing may fail from normal wearout or abnormal wearout, or brinelling. The effect of each mode is identified, as abnormal wearout will cause increased noise and vibration, with rapid wearing of bearing parts and eventual destruction of bearing and seizing of the pump.

In using the analysis the identified effect may be different depending on the purpose for which the analysis is to be used. In reliability analysis the effect considered is the effect on the performance of system function. In maintainability analysis, the effects include the symptoms by which a failure could be identified (as temperature of the bearing) and the additional parts needing replacement due to damage because of the failure of the part. In Safety analysis, the additional effects considered would be damage to adjacent equipment and possible danger to personnel.

Failure mode and effect analysis is a systematic procedure for determining the basic causes of failure and defining actions to minimize their effects. It may be applied at any level of assembly (from complete weapons systems to parts). In each case the mode is described as the way in which the unit fails to perform its function. For a missile system the function of hitting a target may not be performed due to guidance error or incorrect velocity due to early engine shutdown, etc. For a pump, failure to produce the proper volume and pressure of fluid may be due to loss of suction or bearing seizure. In chapter 3 we described the breakdown of functional requirements step by step, identifying functions with hardware that performed the function. In the same way, in Failure Modes and Effects analysis we establish the functions that the equipment is intended to perform describing as modes of failure ways in which the equipment can fail to perform the function. In reliability analysis, the effects are the inverse of the defined function that is the failure mode effect is the failure to perform the required function.

The analysis is performed to isolate and identify weaknesses in the design. The final step in the analysis is the determination of ways to eliminate or reduce the probability of incidence of critical failure modes to improve the design. Since funds and time are never unlimited, corrective action involves the assignment of priorities of effort based on relative seriousness of the consequences (effects) of failures.

1. USES OF FAILURE MODES & EFFECTS ANALYSIS

1.1 APPLICATION TO RELIABILITY PREDICTION

A method used in predicting the reliability of mechanical systems is similar to the method used in predicting the reliability of electronic systems. A reliability block diagram, which is a pictorial representation of a failure effects analysis, is a basic part of each method. In electronic systems, the blocks are identified as parts or components. Failure modes or mechanisms are seldom referred to. In mechanical systems, however, the blocks are identified by modes of failure, for each part or component. In mechanical system reliability predictions, reference is made to "types of failures of parts in specific application" rather than "parts failure rates."

It is evident that an accurate, precise definition of failure is necessary. The definition of component failure is as needed as the definition of system failure, in particular where the components are those parts of the system to be used in the system prediction and failure rate data is available for them. The controlling factor in determining the meaning of component failure is the tolerance of the system to component variation and/or inoperability. This tolerance varies with the type and timing of component performance variation, e.g., a sticking valve may or may not affect system performance, depending on whether the valve sticks open or closed and when the sticking occurs. Therefore, component failures in mechanical systems often cannot be defined except in reference to that system. A brief outline of a method to be used in predicting the reliability of a large mechanical system is as follows:

Step 1. Divide the system into a number of subsystems which can be more easily dealt with. As this prediction method involves predicting the reliability of each subsystem and then recombining these predictions to arrive at the overall system reliability, the division must take place on a functional basis. Careful and precise system and subsystem definition (chapter 4) is a necessary prerequisite. The block diagram is useful in coordinating and recording the functional breakdown. Numbers are usually assigned to the blocks for ease of cross reference. System definition should include time line analysis, environments, and definition of failure at each block level.

Step 2. Make a detailed study of the schematic engineering drawings for each subsystem in order to determine all of the significant modes of failure. Knowledge of the effect of component failure as well as the subsystem and system reaction to failure of the component is necessary. Definition of failure is an essential portion of the analysis, but it cannot be treated in general terms; i.e., failure means operation not in conformity with some well-stated performance requirements.

Step 3. Determine all of the component failure mechanisms which could lead to each of the failure modes. Failure mechanisms are the basic physical causes of failure and failure modes are the reactions to failure mechanisms. Failure modes can result from the occurrence of any one of a set of failure mechanisms or from the simultaneous occurrence of two or more particular failure mechanisms.

Step 4. Make a summary of all the reliability information obtained and analyzed from the design schematic drawings. This is accomplished by tabulating all of the failure modes and making an analysis to demonstrate the relationships between component and system malfunctions. (Figure 12-5).

Step 5. Using the information compiled above, prepare a reliability model in the same manner as in chapter 5.

Step 6. Determine the probabilities of occurrence of the failure modes to be used as numerical inputs. This type of data may be obtained from manufacturers or may be estimated from the prior experience of the engineer. While in most cases, the values of failure rates are approximate, this computation has great power in comparing alternatives. Reference (2) is an excellent example of such a computation.

Step 7. Generate the system reliability prediction utilizing the reliability model and the probabilities associated with the occurrence of each failure mode to arrive at a numerical value representing the overall reliability of the system under investigation.

1.2 APPLICATION TO MAINTAINABILITY PREDICTION

As mentioned in chapter 8 the prediction of a Mean Time to Restore

J79-5 ENGINE FAILURE RATE ANALYSIS

ASSEMBLY NAME COMPRESSOR ROTOR
ASSEMBLY DRAWING NO 107R491C7

ITEM NO	COMPONENT NAME	DRAWING NUMBER	MODE OF POSSIBLE FAILURE	FAIL RAPID OR GRAD	EFFECT ON COMPONENT	EFFECT ON BASIC ENGINE	POWER LOSS EFFECT MAX	MIL	95%	90%	NONE	F/R FAIL 10^6 HR	DESIGN LIFE HRS
IA1c22	Shaft, Hub - Compressor Rotor Front (1 req'd)	615E798P1	Rupture	R	Shaft Breaks	Rotor Failure Ruptured Casing Other Engine Damage or Destruction	X	X	X	X		1	10000
			Yield	G	Unbalance	Compressor Rubs Motor Misalignment Hi Vibs Power Loss Blade Damage	X	X					
			Spline Wear or Shear	G	Wear Spline Shears	Loss of Accessory Drive System Engine Shutdown	X	X					
			Bearing Surface Wear	G	Wear	Rotor Misalignment Compressor Rubs Hi Vibs	X						

DESIGN CONSIDERATIONS

STUB SHAFT, COMPRESSOR ROTOR FRONT

1. Design temperature - 300°F
2. Design Rotational Speed - 7650 RPM
3. Material of Component: Chrome, Molybdenum, Vanadium Alloy Steel, G. E. Specification B5F5, C50T7F

   Material properties at design temperature
   - a. 92% yield strength if 107,000 psi with 10% reduction for material deviations
   - b. Not in creep range
4. Stress calculations covered in Memorandum 60 DM79C-7
5. Part subjected to magnetic particle inspection per material specification. When supplied as a spare, part is subjected to overspeed test of 8100 RPM for 3 minutes with loading comparable to being tested in a compressor rotor assembly.

(MTTR) requires first the identification of the parts subject to failure and an estimate of the probable frequency of such failures. The failure Modes and Effects analysis requires the creation of just such a list. The documentation provides the necessary design discipline for methodically evaluating the probability of failure and the results thereof for trade-off between reliability and maintainability to achieve the system availability requirements. The failure modes approach refines the prediction reliability and maintainability to a consideration of the various mechanisms of failures that may be operable.

Figure 12-7 provides an example of a Failure modes and effects analysis for maintainability evaluation (1). The equipment is a steam turbo-pump. Figure 12-8 continues the analysis of tasks to the individual task elements as outlined in chapter 8.

1.3 APPLICATION TO SAFETY ANALYSIS

The safety aspects of equipment failure are investigated by a Safety analysis. Safety analysis is not restricted to human safety, but includes the effect on the total system, associated or adjacent equipment and personnel in the vicinity either associated with the system or casual. Starting from the identification of the expected failure modes, the effect on the adjacent and associated equipment is evaluated. An example is given in Figure 12-9.

1.4 TIME OF ANALYSIS

Failure modes and effects analysis starts from the top down. System functions and failure modes are first considered in abstrction, then expanded down to the subsystem, component and part level.

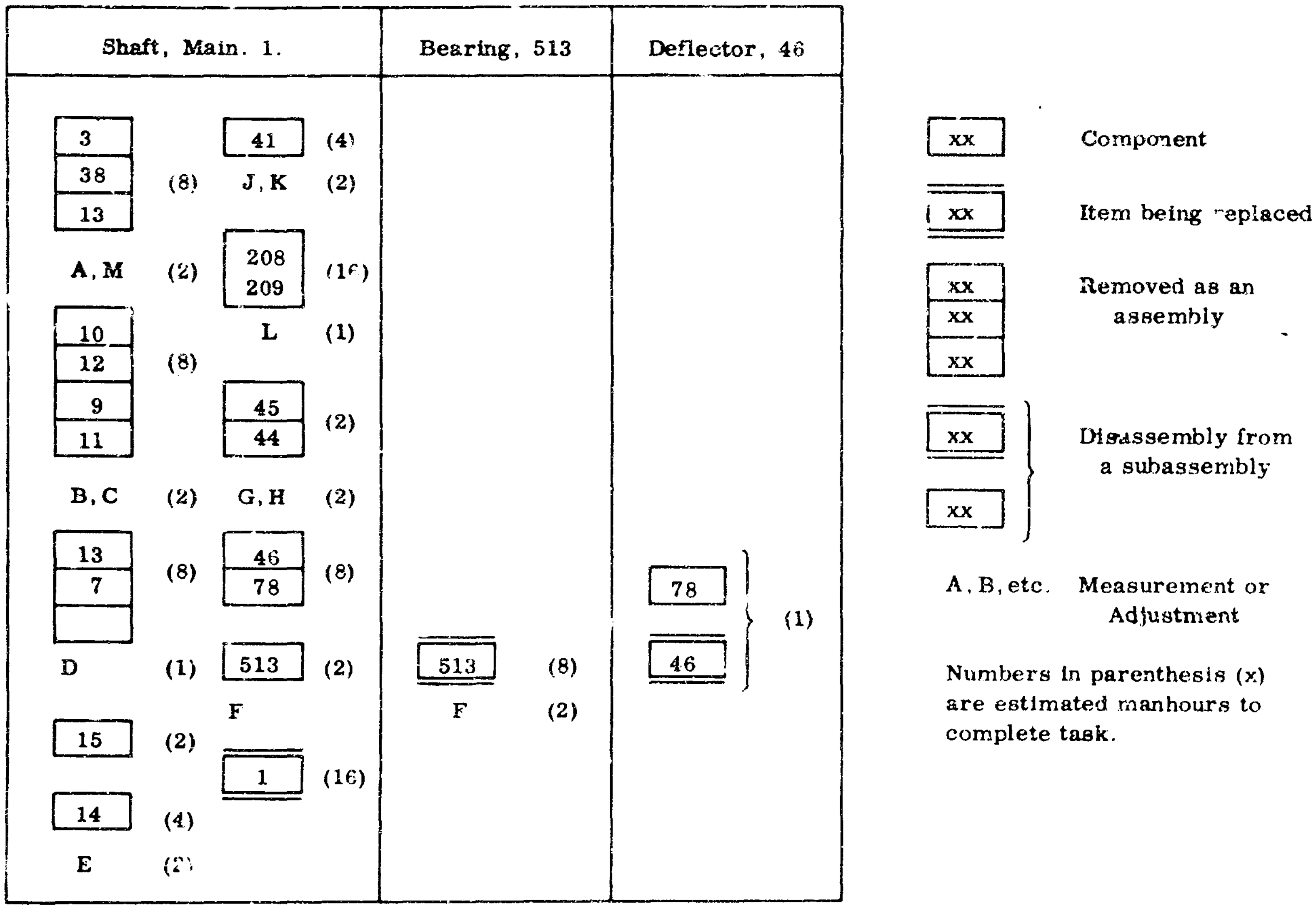
It is initiated during the concept phase of a design, then as the design becomes more clearly defined, is expanded concurrently with the design. The effectiveness of the analysis in system tradeoffs is made possible by its availability at the time design decisions are required. The analysis documentation must be kept dynamic and current with the design clear through the final test and delivery of the equipment. It must be available for use as design changes are proposed to assure that the discipline provided keeps control of the effects of changes in reliability and maintainability.

In the failure effect analysis of the structure, no written analysis accompanies the reliability mode. During the design

FAILURE MODE & EFFECT ANALYSIS

ITEM	NAME	MODE OF FAILURE	CAUSE OF FAILURE	EFFECT OF FAILURE	OTHER COMPONENTS DAMAGED
13 14	WHEEL - TURBINE ASSY. SEGMENT - GUIDE	RUBBING	EXTREME BEARING, THRUST RING OR BALANCE RING WEAR	INCREASED NOISE & VIBRATION WITH BLADE DAMAGE AND POSSIBLY EXTENSIVE DAMAGE TO OTHER COMPONENTS	USUALLY WOULD BE DAMAGED SIMULTANEOUSLY
16	PACKING - THROTTLE VALVE	NORMAL WEAR-OUT	FRICTION WITH VALVE STEM	EXCESSIVE STEAM LEAKAGE	17
		ABNORMAL WEAR	GLAND NUT ADJUSTED TOO TIGHT.	POOR CONTROL. DAMAGED VALVE STEM	
17	VALVE - THROTTLE	NORMAL WEAR-OUT	FRICTION WITH LINER & STEAM EROSION	POOR PRESSURE CONTROL	NONE
		ABNORMAL WEAR	GLAND NUT ADJUSTED TOO TIGHT	EXCESSIVE STEAM LEAKAGE	
18	LINER - THROTTLE VALVE	NORMAL WEAR-OUT	FRICTION WITH THROTTLE VALVE	POOR PRESSURE CONTROL	NONE
MISC.	BOLTS, GASKETS, ETC.	LOOSENESS, LOSS OF MATERIAL, ETC	OVER-STRESS, FATIGUE ETC.	USUALLY REQUIRES SERVICE WHICH CAN BE PERFORMED AT CONVENIENCE	USUALLY NONE

REPLACEMENT TASK DIAGRAM



SAFETY ANALYSIS

Item	Component	Failure Mode	Mode Probability	Failure Effect	Corrective Action
1a13	Reservoir, hydraulic	Burst	.0001	Explosive fragments	Relocate to area C-7; Provide shielding for Electronic equip. Area C-9
				Fire	Relocation minimizes danger of ignit.
				System Failure	Risk acceptable
				Toxic fluid spray	Increase Ventilation
1a14	Accumulator	Burst	.01	Same as reservoir	Relocate to area C-6.

the structure undergoes an analysis involving design and stress calculations, which can be classified as a single failure effect analysis. On the basis of this analysis, the structure is strengthened/redesigned at those points where possible failure will occur. For this reason, it can be stated that the complete structure has been designed to withstand normal loads without failures which will result in loss.

2. IDENTIFICATION OF CRITICAL ITEMS

As we mentioned earlier, the identification of weaknesses in the design is not the end objective. From the analysis,we must determine corrective action to improve the design. The failure modes and effects analysis can be used to assess the relative importance of the various weaknesses isolated to permit intelligent application of effort (time and money) in selecting corrective action. This is performed as follows:

A reliability model is developed for the system. This model serves for definition of the subsystems and identification of the functional components. It is not a functional schematic or an energy flow diagram, but serves for early analysis and to point out "weak links" which detract from the overall mission attainment. A model of a system should have provisions to point out the failure modes which are applicable to redundancy.

2.1 FAILURE EFFECT ANALYSIS

A failure mode and effect analysis is performed for each block in the reliability analysis logic diagram. The failure effect analysis shall indicate the effect of component failure on the subsystem or system performance. In determining the effect of a component failure on sub-system performance, four modes of failure are considered.

1. Premature operation of a component.

2. Failure of a component to operate at prescribed time.

3. Failure of a component to cease operation at a prescribed time.

4. Failure of a component during operation.

Each component is evaluated in this manner for the failure modes that are applicable.

A usual form, Figure 12-12, for the single failure effect analysis, calls for the following critique of each component in the system:

Column	Nomenclature	Description
1	Item	Identify item by name, number required and code designation.
2	Part No.	Federal Stock Number, Classification or Circuit designation, etc.
3	Function	Concise statement of the components function.
4	Failure Mode	Concise statement of the applicable mode(s) of component failure.
5	Failure Effect on System Performance	Full explanation of the effects on the performance of a system and the dependency on time for a given part failure and a justification of the probability of loss statement.
6	Loss Probability (%)	Assign numerical index for the probability of system loss if part fails. Suggested scale Certain Loss - 100%, Probable Loss - 50%, No Effect - 0%.
7	Failure Mode Frequency Ratio	Enter estimated or recorded ratio of failures in each mode to total failures of the part.

2.2 RELIABILITY MODEL INDEXING NUMBERS

A means for direct reference of all items in the reliability model is provided by using an indexing number system. Numbers are used to denote systems, subsystems, assemblies and components. If new items are added or existing items removed, new numbers are assigned to the additions and the existing numbers are discontinued for deleted items.

2.3 CRITICALITY RANKING

A critical items list is by definition based on the item's applicable failure mode, the system loss probability from the failure effect analysis, the item's failure mode frequency ratio, and the item's unreliability associated with the critical failure mode (or modes).

FAILURE MODES & EFFECTS ANALYSIS

ITEM	PART NO.	FUNCTION	FAILURE MODE	FAILURE EFFECT	LOSS PROBABILITY	FREQUENCY RATIO

The failure mode frequency ratio is determined by the failure history of the component. The failure mode frequency ratio (FMFR) is the ratio of the number of failures that occur in a single mode to the total number of failures:

$$\text{FMFR} = \frac{\text{Failures in a single mode}}{\text{Total number of failures}}$$

If a failure history is not available on the particular component in question to determine the failure mode frequency ratio, similar components used in the industry are valuable sources of failure information. Care should be taken that the similar item is used in a similar situation.

The unreliability of a component is determined from its failure rate and its time of operation. Appeal is made to the System Model to determine the environmental conditions during component operation and the time of component operation per mission phase/subphase. The time of operation and the environmental conditions must be known to predict the failure rates and number of failures of components. Once the failure rate is determined it is multiplied by the length of time of operation in the following equation to determine the unreliability:

$$Q = 1 - e^{-\lambda t}$$

where

λ = failure rate
t = time of operation

Criticality Ranking is accomplished by multiplying the three factors together:

$$CR = (P_L)\ (\text{FMFR})\ (Q)$$

where

P_L = probability of loss

FMFR = Failure mode frequency ratio

Q = probability of component failure

2.4 CRITICAL ITEMS LIST

Based on the single failure effect analysis, a critical items list is prepared. These listings are an abstract of those items in the failure effect analysis whose single failure results in the probability of loss, placed in numerical sequence of their criticality ranking. The form for these critical item lists should include the following information:

Column	Nomenclature	Description
1	System	Identify system by indexing number
2	Subsystem	Identify subsystem by indexing number
3	Assembly	Identify Reliability Functional Block by indexing number.
4	Component	Identify component by indexing number.
5	Item	Identify item by name
6	Mode of Failure	Concise statement of the applicable mode of component failure.
7	Loss Effect	The degree of loss probability (should the indicated bype of failure occur).
8	Reaction Time	The estimated time elapsed from a component failure to loss of vehicle (i.e., 0.1, 1, 10, 100, etc. seconds).
9	Criticality Ranking	As computed in paragraph 2.3.

Where a component has more than one mode of failure, which results in the probability of loss, separate entries are made in the critical items list for each mode.

Criticality ranking or classification has the same basic context as the "Levels of Essentiality" criteria for design, materials control and traceability in submarine pressure boundaries (Reference 8).

2.5 APPLICATIONS OF CRITICALITY RANKING

The numerical value of the criticality ranking orders the components by the degree to which they are expected to create problems. A high ranking number indicates that the particular mode of the component needs special attention in the design and, if it cannot be reduced, particular attention paid to the component in manufacture and use. In this way the failure mode analysis may be used to sort out the problems involved in a development program to focus attention on those of the greatest importance.

There isn't one of use who has not been faced with the problem of a program with too little money and too little time to do the job. The analytical technique presented gives early, realistic discrimination criteria which provide greatest assurance the program will meet its requirements with the most effective money expenditure. Given critical items, failure modes, and criticality ranking the components designer becomes concerned with their application in many areas.

Criticality ranking should be used to establish which items should be first to receive review. It should be used to establish the specific areas of investigation in a design review. The review should emphasize where possible "fail safe" operation for critical modes. Where this is not possible redundancy, override controls, and/or failure sensing devices should be incorporated. Since no program is infinitely funded it becomes apparent that the "totem pole" established by criticality ranking provides technical and management judgment criteria for where best to spend program money.

The designer may use critical items to establish which supplier specifications should have more stringent than normal requirements for design, monitoring, and test imposed. Since effectively, the components will undergo very little change once the supplier has delivered an approved part to the system, it is imperative that the design reflect minimum critical failure mode probability. Additionally, the supplier test program should reflect stringent consideration of these characteristics. Such test programs should analyze the effects of combined environmental and critical operational stresses on the hardware in order that the interaction of environments on the hardware will be properly investigated.

Criticality ranking is an excellent discrimination criterion in that it will give the best return for traceability per dollar invested. If program money is too short to provide traceability on all critical items, the criticality ranking index should be used. For instance only those items with a criticality ranking in the upper 15% might be made traceable.

Screening specifications can be established by the designer to assure that any components classed as critical entering the plant will be given a prescribed test or inspection for particular weakness. The items to be screened should be selected from the total critical items list, or if program money is limited, more discriminating selection can be made from the criticality ranking. The characteristics to be inspected should be taken from the failure effect analysis.

Finally, the component designer should establish that the failure reporting system which exists in his company, specifically reports failures on all critical items as such. He should also see that the reporting system stipulates the specific mode in which the component failed. The critical items list should be used to establish which items will receive special expedited attention in the failure reporting and corrective action system. Provision should be incorporated into the reporting system for directly identifying on the report those failure modes which have been established by failure effect analysis as critical. With this type of information plus the normal reliability statistical information surrounding failures and failure anslysis, we can go back to the reliability model and specifically report in critical areas what has in fact happened. This provides for a much more expedited and meaningful analysis.

3. REDUCING EFFECTS OF FAILURE

Failure Modes and Effects Analysis is a design analysis tool used by design and reliability engineers to measure the probabilities of losses associated with failures in a system design.

After the failure mode and effect analysis has been completed, specific items should be summarized to indicate where redesign would improve the reliability through consideration of physical phenomena associated with the potential failure. The redesign may include additional margins of safety, change of materials, process controls, environmental control, or specialized testing to inhibit or control that particular mode of failure.

In order to provide a basis for loss reduction tasks, the designer systematically ranks the failures in terms of their probabilities of failure and their associated losses. Action is taken to prevent the occurrence of high loss failures. High loss failures are attacked by the following schemes:

1. Schemes to prevent component failures. These schemes involve:

   a. Redesign which accomplishes one or more of the following:

1) Reduce the cause of failure
2) Design around failure mode
3) Reduce the effect of failure

b. Modify maintenance schedules or instructions

2. Schemes to prevent the propagation of failure effects. These schemes involve:

a. Monitoring to detect component failures whose effects may cause a loss event, and give suitable warning.

b. Counteraction which accomplishes one or more of the following:

1) Nullifies the effects or conditions leading to loss events or protects agains them. (This includes crew escape, for example).

2) Controls or deactives components, systems, etc., so as to halt generation or propagation of harmful effects.

3) Activates backup or standby units or systems to restore interrupted functions.

4) Replaces failed components if practicable.

4. SUMMARY

The generally accepted definition of reliability implies the assignment of a function or set of tasks for the equipment and associated personnel to perform. Also implied is the definition of a failure state or mode for each task, so that the probability of a system being in one or the other of two exclusive states, success or failure after some period of time, may be estimated. Mechanical reliability is much more a conditional probability than we are used to considering it for electronics. The condition applied is the probability of system failure, given that component failure occurs. Failure modes and effects analysis is the methodical evaluation of this condition. The future path of reliability analysis will include studies in depth on the physics of failure (9) using techniques such as the Failure Modes & Effects Analysis to improve our capability of reliable design.

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Chapter 13

DESIGN FOR RELIABILITY AND MAINTAINABILITY

Chapter 13

DESIGN FOR RELIABILITY AND MAINTAINABILITY

The requirement for very high reliability in weapons systems and critical systems aboard ship runs into two roadblocks -- cost of achievement and time required for development. In establishing the minimum acceptable reliability, the only realistic initial basis is the amount of risk (that the system will not work when required) that the operational commander is willing to accept. Once the risk is established, then the decision to proceed with the development -- or cancel it -- will be made on the basis of priority of need, cost and time. If the acceptable risk is too costly or takes too long to get, it may be desirable to trade reliability for other performance capability.

As we have pointed out before, the efficient way of achieving required reliability is in the initial design. If this can be done, it eliminates many of the costs and delays associated with improving the design to meet the requirements after production starts and many of the costs of problems associated with unreliability of the equipment in operational use (ownership costs).

Reliability can be improved by the designer before the equipment is constructed, before the design is released. This chapter will discuss the accepted approaches the designer can use to achieve the reliability requirement once he has ascertained that it will not otherwise be met in the design. Here are the steps involved:

1. Verify Stated Requirements: Seldom does the bald quantitative statement of required reliability and/or maintainability actually convey the picture needed by the design engineer. There must be thorough discussion of what, physically and specifically, is meant by the numbers. Such discussion usually results in further definition, if not actual change of the stated requirement.

2. Define Unacceptability: A reliability requirement has no meaning until a very clean answer is obtained to the question "What, exactly, constitutes a failure?" This is particularly difficult, and important, regarding the slow degradation of performance found in most systems. How much can a certain performance value, say accuracy, degrade before it is judged a failure? Often it is far more logical to use broader effectiveness criteria, such as "fire-power" (1) instead of the black and white success or failure. The same comments can be made about maintainability, i.e., "What, exactly, constitutes excessive downtime?" And "Why?"

3. Design for Required Reliability: When the requirement (and meaning of failure) is understood, the designer proceeds with tentative design, maintaining a current record of the status of predicted reliability achievement but weighing each decision he must make against the effect that the alternative selected will have on the reliability, in the same way that he does weight, performance capability, cost and delivery. His objective must be to find the optimum combination of performance capability, weight, cost, delivery and reliability that meets his functional requirement. Excess capability over that minimum requirement must be weighed against consequences in terms of the constraints of cost, delivery, etc. If the tentative design for functional capability fails to achieve the required reliability. The special techniques covered in this chapter should be applied to the analysis.

4. Cost-Effectiveness Analysis: Once the design is complete to the extent of specifying major components in detail, a rough cost-effectiveness analysis should be made. Using the techniques of chapter 26, and estimating the cost and time to design and manufacture for the tentative reliability and maintainability requirement values of MTBF and MTTR are selected to optimize the cost effectiveness relationship.

5. Modification and Recycle: As the design progresses to more detailed component level, decisions will be made affecting the reliability and maintainability. These must be evaluated against their effects on total cost and performance requirements, modifying the requirements as necessary to optimize the cost-effectiveness achieved.

1. BASIC RELIABLE DESIGN

As a result of many years and cycles of product design, manufacture, operational experience, and consequent design improvement, most contractors have built up a comprehensive set of standard practices. These practices assure "good" design by the traditional criteria.

But the criteria have changed. Military product complexity has made the previous standards of reliability unacceptable. The loss of system effectiveness, the excessive maintenance cost, and the unavailability of maintenance skills have demanded new reliability criteria.

So in addition to the established standard "good" engineering practices, which are beyond our scope here, basic reliable design, demands the additional formalized practices, many of which are extensions of standard "good" engineering practices, outlined in this section. These are the techniques to be applied to every design to a reliability requirement.

1.1 SIMPLIFICATION TECHNIQUES

Hardly anybody doubts that the way to get real reliability is to make it simple. Like an ash tray. Yet often it will not occur to some computer people that a slide rule, or a pencil and paper, may be adequate and more reliable for some tasks than a computer. Or to system designers that a hydraulic or mechanical system may be much simpler and more reliable for some tasks than an electrical system. Or vice versa.

The average design engineer can get preoccupied with elegance. He has been so encouraged to dream of new ways to get more performance capability, without much regard to reliability or cost, that complexity is accepted as inevitable. But it isn't.

For many years now the "value analysis" techniques have enjoyed growing recognition and acceptance, and they have produced remarkable cost reductions. Generally the procedure is to put a team to work on a released (in manufacture) design, with leadership and instructions (2) through the "information, creative, evaluation, investigation, and reporting" phases. True value analysis, where adequate performance, including Reliability, is maintained by a simpler or less expensive equipment, is not the same as "cost reduction" which may accept reduced performance or even reduced reliability to achieve cost savings.

Virtually all such analyses have been applied to existing designs, to reduce manufacturing cost through substantial simplification. But many times a substantial potential cut in manufacturing cost would be offset by an increased logistic and maintenance cost, so the customer cannot approve it. The real objective to the user is not manufacturing cost reduction, but total cost-effectiveness improvement. And reliability is a major effectiveness element.

Many, if not most, such analyses result in reliability improvement, usually as a byproduct of simplification. So it becomes obvious that the same techniques can be used for deliberate reliability improvement. Following is a typical "value-engineering" phase description, but modified to achieve optimal reliability:

Information Phase: Obtain full information on the design requirements, distinguishing the mandatory from merely desirable, and analyse relative to realistic needs and constraints. Specifically include reliability and maintainability, obtain full information on the proposed or released design, including predicted reliability and maintainability, and acquisition (design & manufacture) and ownership (operation and maintenance) costs, using the best available sources.

Determine the basic and secondary functions of the design, using verb-noun definitions ("transmit torque", "protect surface", "conduct current", etc.) Segregate portions of functions into sequence.

Creative Phase: Use the "brainstorming" technique (3) to list all possible alternative ways of performing the required functions defined above. Avoid negative ("It won't work") judgment while generating as many simple and direct ideas as possible, and recording them. Group action is necessary for triggering ideas in each other.

Evaluation Phase: Evaluate each of the above ideas on the basis of effectiveness, or the best reliability and/or availability that satisfies functional performance requirements. Then evaluate each for total cost of design, manufacture, operation, logistics, and maintenance over the system useful lifetime. Consult with specialists, suppliers, and the customer as necessary. Don't reinvent something already available, if the available one is adequate.

Finally reconstruct the list in decreasing order of apparent ratio of effectiveness to total cost, using quantitative evaluations where feasible. Such ordering decisions are usually meaningful only when comparisons can be made.

Investigation Phase: Using the above basic and secondary functions, determine the reliability, maintainability, and total cost of each. Compare these with target values obtained from other applications of the same function. Consider all standard components available. Work on specifics, not generalities. Select the best one or two ideas on the basis of the detailed analysis.

Reporting Phase: Provide a concise report for design use and documentation, including all data sources, analyses, and logic leading to the selection.

Reference (2) provides a checklist to indicate some approaches for value engineering ideas.

Above all, there is far greater advantage in application of these techniques long before release to manufacture, after which change becomes an order of magnitude or two more costly. They can be used by conceptual, system, and component design engineers on purely paper designs.

1.2 STANDARDIZATION

There is a place in research and development for new ideas, but once the state of the art is advanced, the development should be based on system effectiveness. Many design engineers have resisted standardization, on the ground that it restricts their freedom for exercise of unbridled creativity and "progress" to new things. Now that we have altered the objective from "new things" to "things that keep working", such resistance amounts to poor engineering.

But unless such standards are kept vigilantly up to date with advancing state of the art, they can discourage initiative for new developments. They must be constantly reviewed to add new standards. In the case of new physical hardware standards, very thorough reliability verification must precede their establishment prior to withdrawal (for new design) of obsolete standards. The American Standards Association (4) has been established for national approval of standards sources and for distribution of many standards. Now let's review those pertinent to our needs.

1.2.1 Standard Values: There is often quite substantial economic and reliability benefit in the establishment of standard sizes and values to be used by all contractors and the government to mutual advantage. Chapter 18 provides some detailed examples for parts. Another very familiar example is screw sizes.

But the same principle can apply at any level. We have largely standardized desk heights at 29". Automobile widths are fairly standard. Electrical power systems operate at quite standard voltages and frequencies. The result is higher quantities, and better testing of any one standard design, thus better reliability.

1.2.2 Standard Parts: The establishment of standard parts designs can provide a manufacturers cost reduction, higher reliability, contractors cost reduction, ownership cost reduction, better operational data, and better control of tolerance limits. Details are given in chapter 18.

1.2.3 Standard Components: (such as regulator valves or amplifier circuits) can be either selected from available supplier products or developed by the design engineer, for wide use across a range of higher-level designs. MIL STD 242E provides standard components for electronics use.

The above considerations for parts apply equally well to components, though there are fewer such standards and they are more complex. Many companies maintain a file of thoroughly-proven circuits, which may be either used directly or modified to avoid the unreliability and cost of complete reinvention. But, sadly, the amount of such reinvention in the U. S. must be staggering, for sheer lack of communication and other reasons.

1.2.4 Standard Systems, Subsystems and Major Components (such as a hydraulic servo system), made up of components, can likewise be established and used across many higher-level systems. The Air Force has established a "standard launch vehicle" for this reason. Reliability improvement always results.

1.2.5 Standard Design Methods (such as hull girder strength) can be established for mandatory use by design engineers. Over a period of more than 100 years, by reiterative sequential correction and improvement of design as errors and problems are identified in actual operational use, many technologies have developed standard "rules", "codes", specifications, etc. that are very widely accepted. Basically they are empirical rules that result in high quality, reliability, and safety.

Competition eventually prevents them from approaching overdesign, except to the extent that they sometimes lag state-of-the-art material technology. Nevertheless, adherence to such rules and codes does assure "high" reliability and safety, but does not necessarily achieve the best or optimum value of reliability in relation to acquisition and ownership cost. Here are three examples.

Rules for Building and Classifying Steel Vessels (5) is an excellent compendium of rules, containing the following subjects:

a. Rules for Construction & Classification of Steel Vessels
b. Rules for Construction & Classification of Machinery
c. Rules for Inspection and Testing of Materials
d. Rules for Fire Pumps and Fire Extinguishing Systems
e. Rules for Surveys after Construction
f. Tables of Scantlings
g. Tables of Equipment
h. Load Line Markings

ASME Boiler and Pressure Vessel Code (6) has the objective of providing "reasonably certain protection of life & property, and to provide a margin of deterioration "(wearout reliability)" in service so as to give a reasonably long "(reliability)" safe period of usefulness. Advancements have been recognized. Interpretations are published in the magazine Mechanical Engineering as "Code Cases". The major sections are

1. Power Boilers
2. Material Specifications
4. Low-Pressure Heating Boilers
7. Suggested Rules for Care of Power Boilers
8. Unfired Pressure Vessels
9. Welding Qualifications

National Electrical Safety Code (7) applies to ground installations rather than shipboard, and is legally binding in most U. S. municipalities. It is approved by the American Standards Association (4) as an American Standard. Decisions are made by sectional committees, and approved by the American Standards Association. Its content is:

1. Rules for the installation and maintenance of electrical supply stations.

2. Rules for the installation and maintenance of electric supply and communication lines.

3. Rules for the installation and maintenance of electric utilization equipment (conductors, fuses, circuit breakers, motors & machinery, storage batteries, transformers, lighting, appliances, cranes, elevators, telephone apparatus).

4. Rules for the operation of electric equipment and lines.

5. Rules for radio installation.

1.2.6 Standard Analysis Methods (such as reliability prediction) can be established for applicable use by design and reliability engineers. Such methods are covered in other chapters of this course. Some government agencies and contractors have attempted to establish specifications and mandatory analysis techniques that work nicely for some limited scope of problem, but which do not work for many other problems. Analysis standardization is useful to the extent that its applicability limitations are recognized.

1.2.7 Drafting Standards help to assure that drawings and specifications are consistent, legible, and complete, thus minimizing human error and consequent system unreliability.

1.2.8 The Military Standards System (Mil-Std) provides many standards for computation, analysis and management. For the major reliability and maintainability standards, see Chapter 17.

1.3 STRESS/STRENGTH DESIGN

The classical and completely valid approach to design is to give every part enough strength to handle the worst stress it will encounter. Hundreds of books such as Mil-Hbk-5 (10) are available providing data on the strength of materials, and some of these provide limited data on strength degradation with time, resulting from fatigue.

But when we come to design for a specified reliability, the traditional and common use of "safety factors" and "safety margins" is inadequate. We have to design in such a way that we can at least roughly predict either (a) the MTBF of the design in operational use, or failing that (b) the probability that stress will not exceed strength. At least three approaches have been developed:

1.3.1 Derating: Intuitively every design engineer feels that reliability is improved by using parts rated much higher than the expected stress. That is, he "derates" the parts for his application. It is equivalent to increasing the "safety factor". Unfortunately this practice also increases cost, weight, and volume. If operational experience shows no failures, he never knows how much, if any, unnecessary cost, weight and volume he has incurred. We are all aware of such examples of "overdesign". Nevertheless, judicious derating is a powerful aid to reliability. Parts derating is covered in Chapter 18.

1.3.2 Reliability Margin: In the absence of adequate failure rate data, which absence is common in mechanical and structural fields to date, a second approach is available. Robert Lusser originally proposed it in 1957. Kececioglu recently published a technical summary (10) of the techniques, with many references. The method is covered in detail in Chapter 7.

Nearly all design involves many assumptions to avoid unjustifiable volume of analysis or test cost. The outlined approach permits design to predictable reliability, but does not insure against design errors of assumption, analysis, omission, etc. Verification is mandatory if high reliability is to be achieved. Possible activities in the verification area should include:

1. Conduct independent Reliability Margin analysis: An

independent reliability analysis of the design, by analysts other than those who conducted the design prediction, pays dividends. A fresh viewpoint, alternative analytical methods, etc., nearly always turn up details worth changing before the design is too far committed to manufacture.

2. Conduct tests to failure for critical margins: When the above design approach is used, probably all critical margins have become well-known to the design engineer. Listing the first dozen or two of these in the order of increasing Reliability Margin, he can then estimate what a series of simple tests to failure for each would involve in cost and time. Or it may be feasible and more conclusive to design fewer tests to failure of a higher system level to achieve the required verification. Ten lunar Excursion Module prototypes, for example, will be used for such tests to failure.

3. Modify the design and/or material: Independent analysis and test to failure are of course worthless until their lessons are translated to design improvement. Surprisingly, this is sometimes resisted.

1.3.3 Stress/Strength Testing: When distribution data is not obtainable for the above analytical approach, yet the design reliability is a critical matter, it may be necessary to conduct experimental tests. Tests to determine stress distribution in a prototype are fairly straightforward and non-destructive, using instrumentation such as strain gages, plastic models and polarized light, etc. To the extent that such tests can simulate the manufacturing variances, operational environment, external stresses, and time effects, the results can be quite dependable.

But tests of strength distribution are much more difficult, expensive, and time consuming. If the design engineer can identify specific local areas of critical doubt, a series of comparatively simple tests can be designed, wherein stress is repeatedly increased until failure occurs, providing a rough strength distribution curve for the local area. On the other hand it may be more convincing, if not more economical to test an entire prototype in the same manner, so that all interactions are accounted for, repairing failures each time they occur. Of course as strength inadequacies are thus brought to light, the design is changed to get required strength.

Such stress/strength testing should not be confused with simple "overstress" testing, which determines only that the design does not fail at some specified stress above the operational level. Overstress testing does not generally determine strength.

1.4 TOLERANCE EVALUATION

In quantity manufacture, all parts characteristics have statistical distributions. That is, any one characteristic (such as length or resistance) has a nominal or mean value, and a variance above and below it. We call the extreme values of the variance "tolerances". These distributions are basically affected by manufacturing lot, and by techniques for selection of close-tolerance parts out of wide-tolerance lots.

In addition to such manufacturing variance there is application variance regardless of quantity. That is, there are distributions of each characteristic resulting from environment (temperature, etc.) stress (pressure, voltage, etc.), and time (cold flow, drift, aging, etc.). Such distributions or tolerances must be added to the manufacturing distributions or tolerances in order to determine the real operational distribution.

A design is never complete until the design engineer has made sure that the distributions or tolerances cannot combine in such a way as to interfere with the intended function. In a complex circuit, mechanism, or structure it is necessary to consider the overall effect of the expected range of manufacturing variance, operational environment and all stresses, and the effect of time. Three general types of evaluation are used for this purpose:

1.4.1 Worst-Case Tolerance Analysis: For maximum producibility and reliability the design engineer often attempts to design the equipment to perform properly with all parts simultaneously at their tolerance limits, and in such a direction as to produce the greatest deviation of nominal performance. For relatively simple configurations this is usually easy to do, and quite effective.

But for the more complex mechanisms and circuits, such an attempt will often fail because even the best and highest precision parts will not have small enough tolerances. In other cases the tolerance problem may be so solved, but at the expense of complicating the mechanism or circuit to the extent that overall reliability suffers.

Some standard computer programs are available for such worst-case analysis of complex systems But it should be kept in mind that worst-case analysis computes a situation which will probably never occur, and which therefore leads to tighter tolerances, higher manufacturing costs, and usually higher reliability than are really needed. The design will be extremely reliable, but not very cost-effective.

1.4.2 Statistical Tolerance Analysis. Fortunately the probability that all the parts will exist at their maximum tolerances simultaneously is very remote. Let us investigate the manner in which the individual parts tolerances affect the over-all tolerance. This effect of individual tolerance forms the basis for the statistical approach to circuit design. The following material is from reference (11) which is an abstract of detail procedures in reference (8). See also references (12, 13, 14).

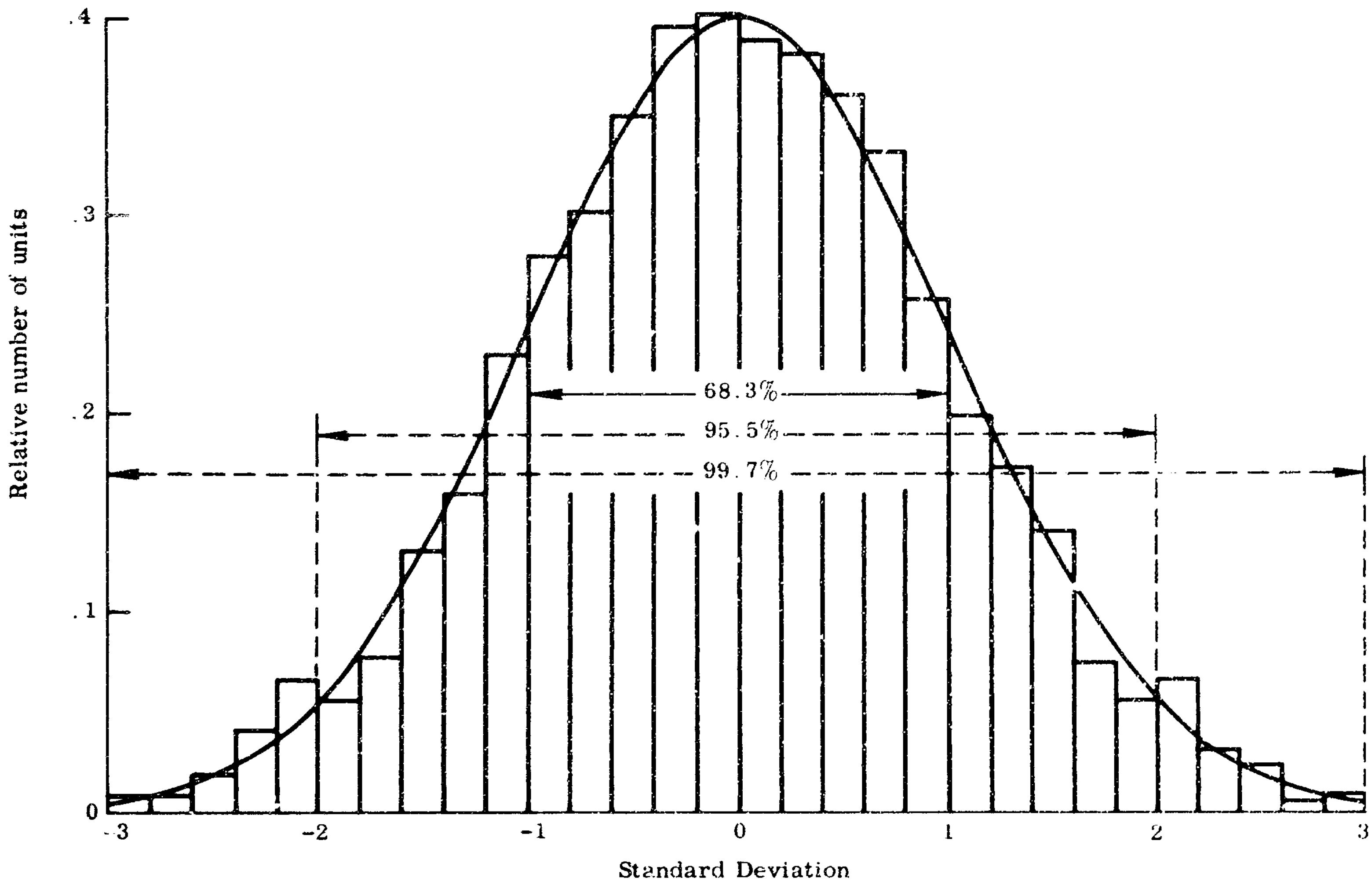
It is well known that many production parts have a normal or Gaussian frequency distribution as illustrated in the following example. Suppose that measurements were made of the values of a large quantity of capacitors of the same nominal value and ±10% tolerance. Plotting vertically, the number of capacitors in each 1% interval of capacitance will usually result in a histogram similar to the one shown in Figure 13-14. As the quantity of capacitors measured is increased and the capacitance interval is narrowed, the envelope of the histogram will form a normal distribution curve as shown. This curve is symmetrical about the average and asymptotic at the base.

The total area under the curve represents all the capacitors. The area bounded by $\pm\sigma$ covers 68.3% of the total area; that is, 68.3% of the capacitors are included by $\pm\sigma$. About 95.5% of the capacitors are included by $\pm 2\sigma$ and 99.7% are included by $\pm 3\sigma$. The manufacturing tolerance will usually correspond to $\pm 3\sigma$ or greater, depending upon the degree of production control; that is, 0.3% or less of the parts usually will be out of tolerance. Of course, additional variations in capacitance will result when the capacitors are subjected to conditions of operation and environment.

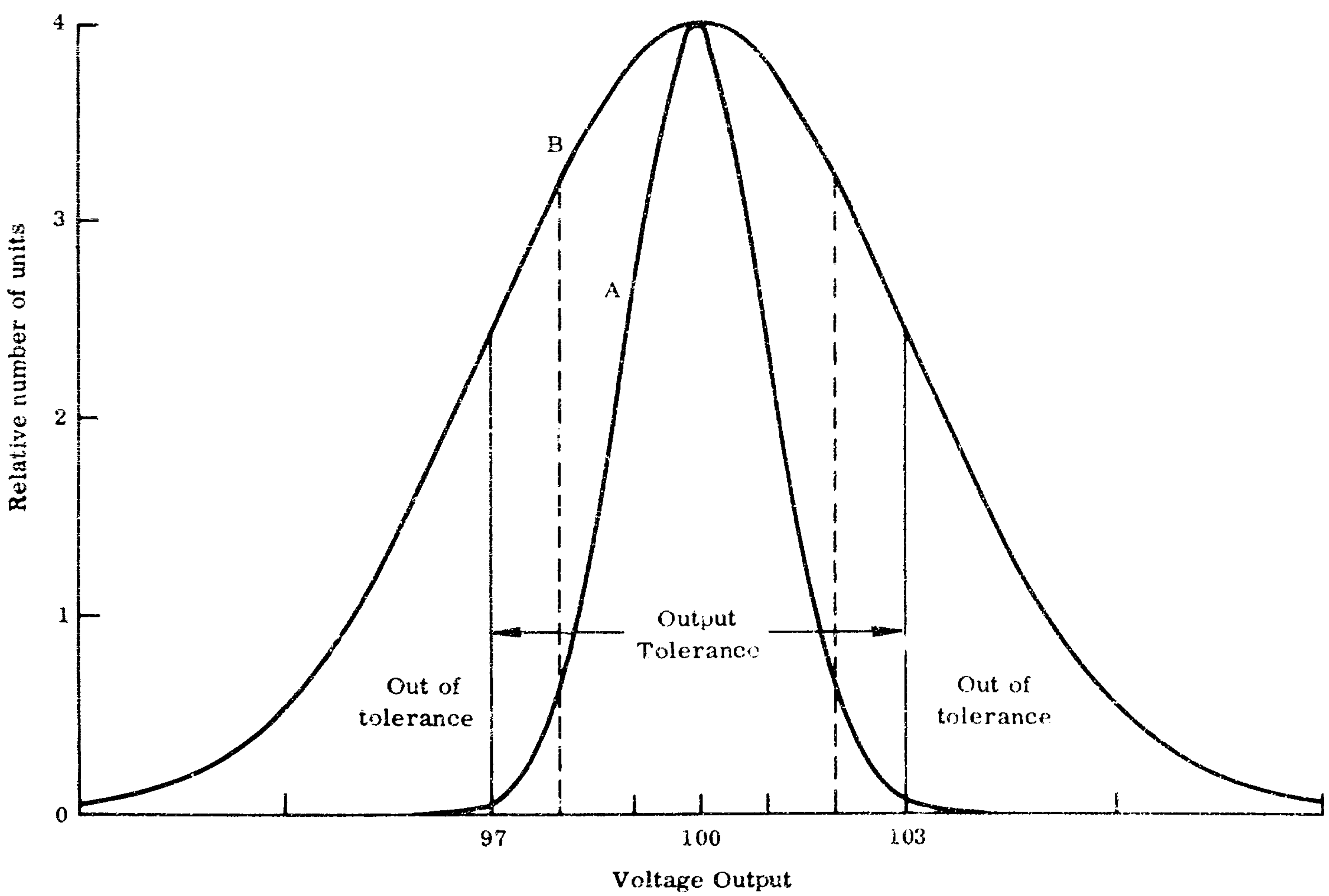
Even when individual parts values are not normally distributed, their associated circuit output variations will be nearly normally distributed because of combination effects.

It is important that engineers design hardware that meets tolerance specifications in a very high percentage of the equipments built, both from production and reliability standpoints. To illustrate with an oversimplified example, consider a circuit which, in production, must meet a tolerance of 97 to 103 volts output (Figure 13-15). If the actual design allows production to meet this specification to the 3-sigma limits of a typical normal distribution as shown in Figure 13-15(A), there are only 3 out of 1,000 circuits

NORMAL DENSITY FUNCTION



DESIGN TOLERANCES



which require parts changes to meet the specification.

In many instances, however, designs have allowed production to meet the specification only to the 1-sigma limits, as shown in Figure 13-15(B), whence 100 times as many circuits (31.7%) require costly parts changes involving special selection to meet the specification. This results in a nearly rectangular distribution. With this distribution, there are, of course, many more circuits near the specification limits than in the case of Figure 13-15(A).

If severe environments and operating conditions allow only equipments using those circuits measuring between 98 and 102 volts on the production line to "hit the target", about 30% of the equipments using the circuits of Figure 13-15(B) would fail to do their job, compared to only 4% failing with the circuits of Figure 13-15(A). Thus, much higher reliability results in the latter case, even though the circuits met the specification in both cases. From this example, it is easy to see why we are striving for designs to meet at least the 3-sigma limits for their tolerances without rework, both from production and reliability standpoints.

Let us now see, with the aid of the following examples, how tolerances combine to meet the foregoing objectives.

<u>Example 1: Series Resistance Tolerance:</u> When parts values having a normal frequency distribution are combined, the resultant value will exhibit a tolerance advantage. If three such resistors (3,000 ohms, 2,000 ohms, and 1,000 ohms) each of $\pm$10% tolerance are connected in series, the total resistance expected will be:

$$R_S = 6{,}000 \pm \sqrt{300^2 + 200^2 + 100^2} = 6{,}000 \pm 374 \text{ ohms} = 6{,}000 \pm 6.2\%$$

This will be the combined value with the same probability that each resistor range is $\pm$10%; that is, if the tolerance of each resistor is $\pm$10% in 99.9% of the cases, the sum will be 6,000 $\pm$ 374 ohms in 99.9% of the cases. If more resistors are combined, the over-all tolerance improvement will be greater.

$$\text{Combined tolerance} = t_S = \sqrt{t_1^2 + t_2^2 + t_3^2 + \ldots t_n^2}$$

where t_1, t_2, etc., are the individual tolerances, each of which must contain the same number of sigmas. The resulting combined tolerance will also contain this same number of standard deviations. That is, if

$t_1 = A\sigma_1$, $t_2 = A\sigma_2$, etc. where A is some constant.

then

$$t_{sum} = A\sigma_{sum}$$

Thus, it is seen that the equation for t_s above is derived from the more basic equation

$$\sigma_s = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots \sigma_n^2}$$

It is preferable, wherever possible, to express a result as a sum of values to utilize the mathematics of probability more easily. In many cases, this can be done by using the logarithms of values which are to be multiplied or divided and by using the reciprocal of values which combine in the same manner as parallel resistances.

Example 2: 7-Stage I-F Amplifier Gain Variations. Let us check a 7-stage i-f amplifier for gain limits, where each stage uses the same tube type with a bogey transconductance of 5,000 microhms and a 1-kilohm composition load resistor (very lightly loaded). The tube and resistor variations used are those given in reference (8), wherein the ± values are the 3-sigma limits for normal distributions centered about the values preceding them.

For Lowest Expected Gain:

Tube Contribution:

(g_m low by 21% ±15%)

$g_m = 5{,}000\ (0.79 \pm 0.15) = 3{,}950 \pm 750$

Gain per stage (nominal r_1) $= g_m r_1 = 3.95 \pm 0.75 = 11.9 \pm 1.7$ db

Tube and Resistor Contribution:

r_1 low by 8.5% ± 6.7% contributes a decrease of 0.77 db ± 0.64 db

Then gain perstage = 11.9 db − 0.77 db ± 1.7 db ± 0.64 db

$= 11.13 \pm \sqrt{1.7^2 + 0.64^2}$ db

$$7\text{-stage gain} = 7 \times 11.13 \pm \sqrt{7(1.7^2 + 0.64^2)}\,\text{db} = 77.9 \pm 4.8\ \text{db}$$

For Highest Expected Gain:

Tube Contribution:

(g_m high by 15% $\pm$ 15%)

$$g_m = 5{,}000\ (1.15 \pm 0.15) = 5{,}750 \pm 750$$

$$\text{Gain perstage (nominal } r_1) = g_m r_1 = 5.75 \pm 0.75 = 15.2 \pm 1.1\ \text{db}$$

Tube and Resistor Contribution:

r_1 high by 12% $\pm$ 5.4% contributes an increase of 1 db $\pm$ 0.4 db

$$\text{Then gain perstage} = 15.2 + 1 \pm 1.1 \pm 0.4\ \text{db} = 16.2 \pm \sqrt{1.1^2 \pm 0.4^2}\ \text{db}$$

$$7\text{-stage gain} = 7 \times 16.2 \pm \sqrt{7(1.1^2 \pm 0.4^2)}\,\text{db} = 113.4 \pm 3.1\ \text{db}$$

Therefore, the gain of this amplifier under typical production and operating conditions is expected to lie between 73.1 db and 116.5 db. During the past several years in which i-f strips have been in production at Motorola, this gain variation has been shown.

Through use of these principles, other more complex circuits have been successfully investigated to determine whether or not they had adequate safety margins to meet their required tolerances. This approach has been valuable not only in avoiding production of unreliable equipment, but also in avoiding the wasted breadboarding of circuits which are incapable of performing consistently within required limits.

Reference (8) provides some electronic part variance data updated to March 1963. Some parts tolerance data is provided in chapter 18.

The design engineer can adjust part tolerances (distributions) until the probability of acceptable component performance is at least equal to required component reliability. Rigorous such analysis can be very complex, often requiring a computer. But it leads to actually needed part tolerances, minimum manufacturing cost, and required reliability. The design will approach the correct reliability needed for best cost-effectiveness, but not necessarily the highest possible reliability.

1.4.3 Marginal Checking has been developed (reference 15) to (a) make graphically clear, in an explicit quantitative way, what tolerance a given circuit has to variations in its components, and (b) provide a method, usable in the later systems phase, of preventive maintenance that will adequately cope with the problems of preventive maintenance that will adequately cope with the problems of component deterioration. Such a method has been extensively used in the design phases of large real-time control systems, as well as in day-by-day operation of such systems.

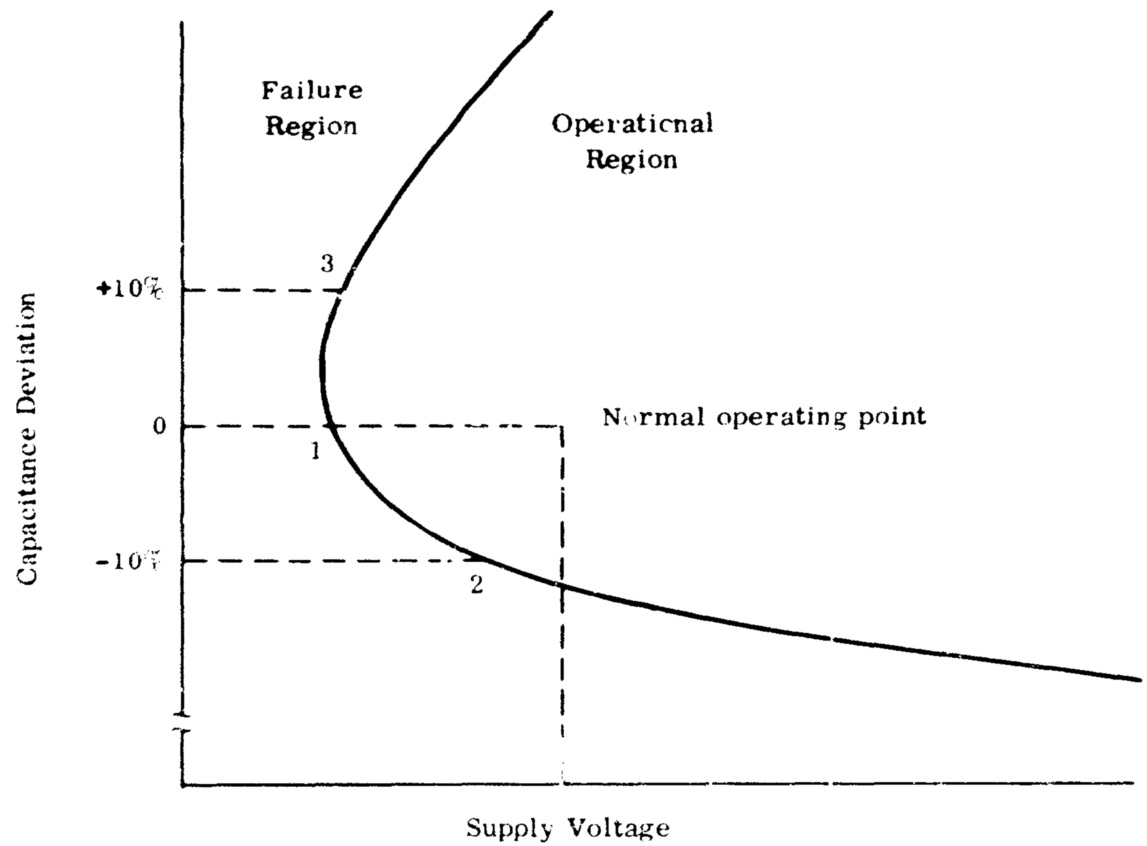
This section discusses the use of marginal checking in the design phase. The allowable variation of a component is determined as a function of a selected circuit parameter, usually a supply voltage. This measures the margins or circuit performance in terms of the marginal-checking parameter.

In practice, the tolerance of one of the components in the circuit is plotted against the variation in this marginal-checking parameter, as illustrated in Figure 13-20. The intersection of mean-value and normal marginal-checking parameter lines near the center of the parabola indicates the operating point of the circuit - normal voltage on the circuit and normal value of the components. By considering the supply voltage as the marginal-checking parameter and lowering it, a point is plotted on the contour line where the circuit fails to perform. This failure can be defined as the point at which the function of the circuit deviates from that prescribed in the specification. In an oscillator, for instance, the point at which the frequency shifts out of tolerance can be considered failure; in a flip-flop, the point at which some standard pulse fails to switch the position may be failure.

Changing the tolerance on the component by some factor such as 10 per cent marginal-checking voltage will result in a different failure point, such as Point 2 on the curve. Raising the tolerance of the component 10 per cent, another failure point, Point 3, can be plotted. Continuing this study, a contour representing the locus of the failure point of the circuit to tolerance in componentry, as a function of some marginal-checking parameter, can be drawn enclosing an area of reliable operation. This sort of study often results in finding that the contour is not symmetrical about the operating point, and that wide safety margins occur on one side but very narrow margins occur on the other.

It is interesting to note that such contours change radically

MARGINAL CHECKING



with the type of circuit. In most cases, the contour would be a closed loop if the marginal-checking parameters could be varied far enough without damaging the components. It is probably evident that plotting the curves and varying each of the components in even a moderately complex circuit represents a rather long and tedious study. However the designer can hardly afford to be ignorant of how much margin a circuit has before it will fail. The acceptability of the circuit to the system can be based only on such knowledge.

On an experimental model or "breadboard" the effects of manufacturing variance, cold flow, drift, or aging can be simulated by insertion of appropriate spacers or resistors, by altering voltages or currents, etc. For example lowering electron tube heater voltage simulates cathode deterioration, with corresponding effect upon transconductance. Diode forward resistance may be simulated by adding series resistors. Transistors having tolerance limit values can be substituted to study the effects. Brakes can be added to study the effect of wearout that leads to friction.

To the extent that such tests can be conducted under true operational environment and stress, they can be very useful. But the analytical approaches are usually better able to fully account for all manufacturing, environment, stress, and time factors, as well as to provide derivative insight, and they are usually less costly.

1.5 FAILURE RATE PREDICTION

When failure rate information is obtainable for any of the parts or components comprising the tentative design, basic reliable design demands that it be obtained and used as a tradeoff consideration in each design decision.

1.5.1 "Generic" Data in Design: For a first approximation the sources outlined in chapter 5 can be used to predict the designed component failure rate. If the resulting prediction is an order of magnitude higher (say 5-to-1 or 20-to-1) than the required failure rate, then, in spite of the data variability, the design probably will have excessive failure rate. The designer then has to do something to his design to get it down, and the list of failure rates on his design parts list will indicate where to look for improvement.

For a particular design, a search of the reliability literature will often turn up better data, particularly for parts and components not covered by the above sources.

1.5.2 Source Data for Design: Since the above generic data tells the design engineer very little about the failure rates of the specific parts or components he wants to use, he must get it elsewhere. Some contractors have data collection systems that collect failure mode, operating time or cycles, stress, and environment data on all parts and components they use. When the accumulated time or cycles is great enough, such data will serve very well.

Most parts and component manufacturers doing business with the military have now had to collect such data on their own products, from their own tests, from their customers, or from the military users. Therefore a prime source of such data is the manufacturer. For competitive reasons he may refuse to publish it, but it is usually obtainable on a confidential or informal basis, not to be quoted. Another way to get it is to ask for a quotation on delivery of a number of parts that are guaranteed to meet the specified reliability. If the specified value is not realistic, one will quickly find out what is.

Another source is the manufacturers customers who may also be less biased and more willing to provide it.

In any event, the contractors design engineer has to systematically look for such specific data among such sources. It will not be found in convenient handbooks.

1.5.3 Test Data: If satisfactory data cannot be obtained as above, the contractor may need to conduct tests, or ask the suppliers to do it. See chapters 7 and 11. On the other hand the reliability requirement may be so high that such tests would be too costly or take too long.

1.6 HUMAN ENGINEERING

All system and hardware designs are operated by people, and people make mistakes. Many such mistakes result in failure of the system to perform its function. Therefore human reliability is just as important to system reliability as hardware reliability, and often more so. The reliability of people, however, can be remarkably influenced by the design engineer in many ways, for which detailed treatment is given in chapters 8 and 14.

1.7 FAILURE CAUSE & EFFECT AVOIDANCE

Chapter 12 provides the detailed techniques of Failure Modes & Effects analysis. This is a very powerful tool that works both qualitatively and quantitatively. It provides remarkable visibility to the design engineer, so that he can design around potential failures.

Each time a failure mode and its effect are established as above, there are two avenues for potential reliability improvement. One is to examine what would cause the particular failure mode, and to explore the possible ways that the design can be altered to reduce or eliminate the cause without causing some other failure mode or effect. It works more frequently than might be imagined.

The other avenue is to examine the effects of each failure mode, and to explore the possible ways that the design can be altered to reduce or eliminate adverse effects without causing some other failure mode or effect. This is the more commonly stated objective of such analysis.

1.8 PREVENTIVE MAINTENANCE

Whenever a part or component has a "wearout" failure rate characteristic, meaning that after some period of operation its failure rate begins to rise, obviously reliability is preserved by timely preventive maintenance. Examples are (a) friction interfaces such as cams, (b) members under high fatigue stress, (c) devices exposed to corrosion, etc.

The usual experience with manufacturers recommended preventive maintenance schedules, both in and outside the Navy, is that they are not religiously followed. So failures occur. Therefore if reliability is a prime objective, the contractors design engineer must make every effort to avoid the need for preventive maintenance. Obviously this is not always possible, but all such items must be included as failure modes in chapter 12.

Where the need for preventive maintenance cannot be avoided, the design should provide for the longest possible period between such maintenance, and above all must be consistent with the overall maintenance policy of section 4.9, the availability of skills, and accessibility as in section 4.6.

Finally, the technical manuals must emphatically call out the schedule and <u>importance</u> of such maintenance to reliability, and it's a good idea to spot prominent labels like "Lube with xxx every 30 days" next to the fitting on the equipment itself.

Failure to adhere to preventive maintenance schedules will always reduce reliability.

1.9 PRODUCIBILITY

It is often alleged by contractors manufacturing departments, sometimes with an element of truth, that "engineering is just trying to design it so we can't make it." Or what might be worse, "We'll make it that way regardless of cost or consequences." The consequences are often unreliability. What are the elements of producibility?

1.9.1 Procurability: The commonest complaint is specification of purchased components in such a way that they are obtainable from only one source. This places the procurement people at the mercy of the supplier who can simply say "This is the best reliability I can provide, but I can't guarantee what it is. Take it or leave it." Specifications must be so written that the supplier knows what reliability he will have to prove to get paid, and knows that one or two competitors can do it if he does not. Thus the reliability specification must be truly achievable, verifiable, and competitive.

1.9.2 Manufacturability: A good design engineer must know the machine tool capability of his factory, and the standard parts with which it has experience. Design within this capability and experience permits the factory to very closely approach the inherent design reliability.

Conversely design requiring complex special tooling, special parts, and exotic materials with which the factory has no experience inevitably leads to poor reliability while the factory learns how to deal with them. And the factory will not have discovered all problems prior to delivery of the first product.

1.9.3 Testability: Frequently a design is such that it cannot be adequately tested to some vital specification, an obvious opportunity for unreliability. Design review (chapter 15) must make sure that the expected assembly and test sequence is such that every specification can be tested. Of course this is particularly true for reliability verification tests (chapter 11).

1.10 SUPPLIER EVALUATION & CONTROL

The contractors design engineer is completely responsible for seeing that his design meets specifications in every respect. Since a large part of most designs consists of components procured from suppliers, part of his job is seeing that they too understand and can comply with the reliability requirements.

Most contractors supplier survey systems evaluate the suppliers "reliability program", but do not evaluate the supplier design engineers knowledge of reliability technology and the design steps he is obliged to take on the specific design. Therefore it is up to the contractors design engineer, with the assistance of reliability engineers, to satisfy himself that the delivered component will arrive with achieved and verified reliability. There is no substitute for personal engineering contact.

Detailed information on Supplier Control will be found in chapter 1?.

2. RELIABILITY IMPROVEMENT

When "good" design practices are used, and the above basic reliable design techniques are used, the contractors design engineer is often faced with the realization that his design still does not have adequate reliability. This section lists the "strong measures", usually expensive and time consuming, that he can consider next.

When the design is as simple as it can get, and its parts are of the highest available reliability, but the predicted component or system reliability is still far from the actual requirement, what to do? Let's first list some things not to do, though they are quite commonly encountered:

Do not let the contractor ignore the requirements, if it was determined carefully via cost-effectiveness analysis at the next and higher levels. It's just as important as a horsepower or voltage requirement. If the higher reliability is in fact not achievable (seldom the case) then the analysis might show that the maintainability requirement must be changed.

Do not let the contractor tell himself (or others) that "well I'm very experienced in this field, and if this is the best I can do, no one can ask for more." Someone can and had better, if the system is to work as planned.

Do not let the contractor raise the predicted parts reliability to make it come out right, gambling that the parts reliability will be better when it's built. Experience shows that typical MTBF growth is only about 20% per year.

Do not ignore the potential advantage of judicious redundancy, whose reliability benefit can be phenomenal relative to the cost and weight, if any, added.

Before embarking on the following program, however, the designer should seriously ask "Is this trip necessary?" He should go back to the higher level source of the reliability specification, explaining what is likely to be involved, to find out whether the specification can be relaxed. Often as not it may be found that the excess failure rate can be absorbed in some other part of the system that now appears to have better than anticipated reliability. Or sometimes he may find that the specification was not so firm after all, when the achievement cost and time are considered.

2.1 EVALUATION TESTS

Perhaps the commonest approach to reliability improvement is the construction of one or more models, prototypes, or "breadboards" of the questionable portion of the design. Or the procurement of a test quantity of components.

If stress/strength margin is the primary question, stresses are measured under simulated load and environment, and strength obtained by testing a number of units to failure. If tolerance buildup is the question, a systematic worst-case simulation is conducted. If human compatibility is the question, tests are conducted using operators or maintenance people. If failure effect is the question, failures are simulated. If producibility is the question, manufacture and assembly of the models will show it.

If failure rate prediction is the question, it may or may not be feasible to conduct life tests, depending upon mission time, quantity cost, etc. "Accelerated" tests are frequently considered, but unless a bona-fide correlation between operational and overstress can be proven, they are meaningless. For example transistor failure rates at excessive temperatures can be easily correlated to operational temperature, but this provides little or no information about random failure rates for all causes at operational temperature.

In all the above tests, the objective is to (a) determine precisely where and how it fails, (b) modify the design to avoid the cause or effect, and (c) recycle until the required reliability is achieved (see chapter 11).

2.2 LOCAL ENVIRONMENT CONTROL

Often it becomes apparent during design that the severe environment is about all that prevents achieving the required reliability. The design engineer is faced with a choice between improving the component to withstand the environment, or improving the environment to satisfy the component. Such local environment control nearly always adds weight, space and cost, so he has to evaluate the tradeoff on the basis of cost-effectiveness.

Often ignored by the contractors design engineer is the harmful effect of factory, transportation and installation environments, as opposed to operational environment. Cross-country trucking temperatures can get very high, and shock levels often far exceed the operational specification. Obviously improved packaging and special handling instructions may be necessary to preserve high reliability.

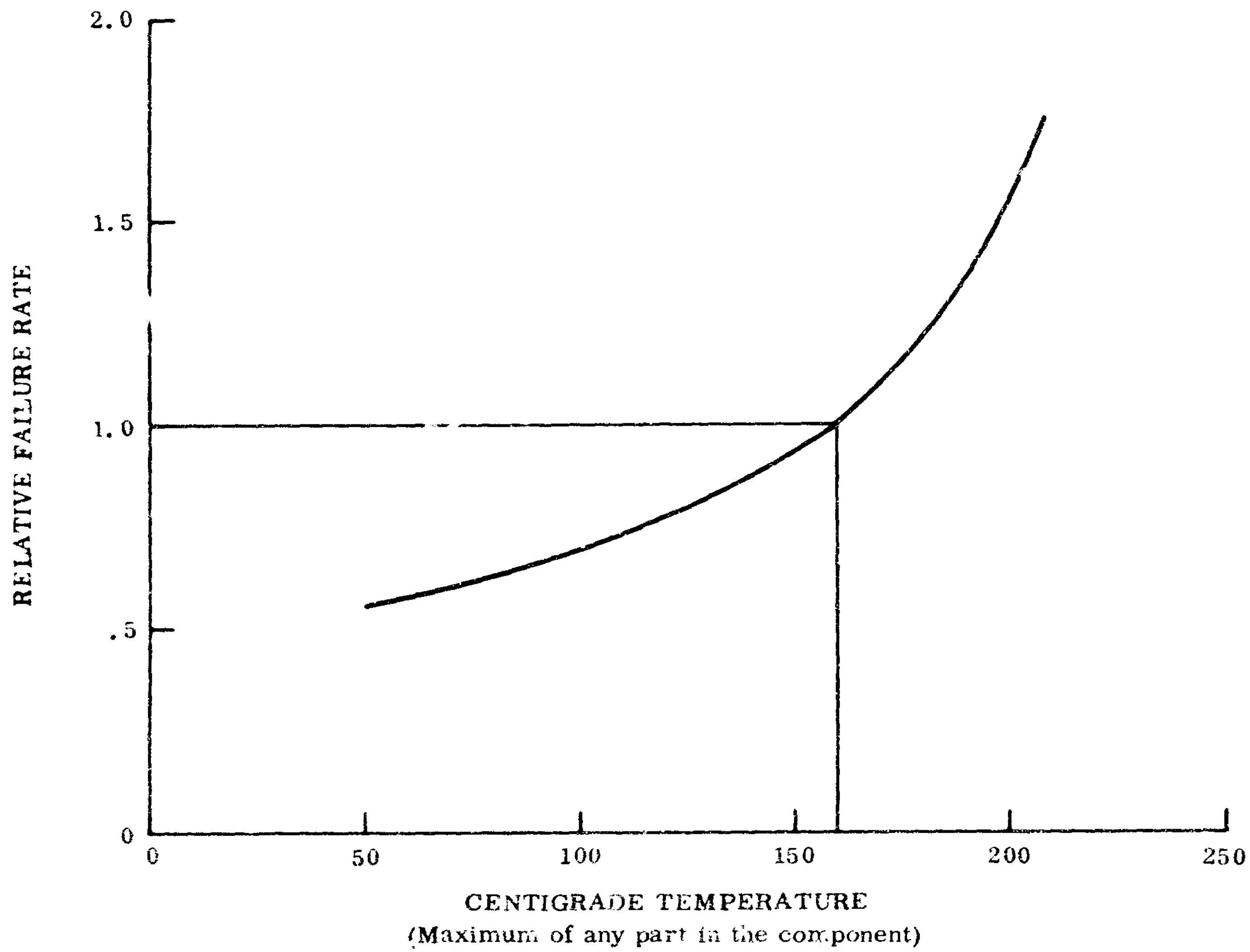
Here are some examples of local environment control.

2.2.1 Temperature: Figure 13-28 reproduced from reference (8) shows the generalized effect of temperature on the failure rate of electronic parts. Similar curves are available for many specific electronic parts, and can be generated for many mechanical parts. Thus to improve reliability the design engineer can consider such provisions as freer convection, radiation fins, forced air or water cooling, better heat source distribution, reduction of heat generation, and even conventional refrigeration. Of course as the means of temperature control becomes more complex, and its own reliability is taken into account, a point of diminishing returns can be reached.

2.2.2 Humidity: High-impedance electronic circuits are particularly sensitive to humidity, but low-impedance transistor circuits are seldom affected. Corrosion of mechanical and electrical components is of course promoted by humidity. Control can be effected by hermetic sealing, dessicants, air flow, heaters, refrigeration, etc.

2.2.3 Vibration & Shock: General displacement of the vacuum tube by semiconductors has greatly improved electronic circuit reliability in vibration environment. Mechanisms are subject to wearout unless designed for the vibration. Shock mounting can be used to control the environment, if all possible excitation

COMPONENT FAILURE RATE



frequencies are considered.

2.2.4 Radiation: Semiconductors are still very sensitive to radiation, the effect being a progressive deterioration. So are people. The only controls are very heavy and bulky shields.

2.3 FAILURE PREDICTION DEVICES:

Sometimes when there seems no feasible way to improve reliability of the components, and redundancy does not improve cost-effectiveness, ways can still be found to detect an approaching failure in time to head it off. The result is effective reliability improvement. Here are some examples:

2.3.1 Temperature: We are all familiar with the widespread use of temperature as a dependable indicator of trouble in diesel engines, people, etc. Thermometers and thermocouples are designed into engine systems so that their operators can monitor well-being and take steps to keep them from failing. Contacts may be used to sound or flash alarm. Without such indicators on manually-operated or maintained systems, they would be much less reliable, and their failures more costly. Therefore the lesson is to look for less-conventional places where temperature monitoring can achieve still higher reliability.

2.3.2 Sound: Some mechanical systems telegraph incipient failure to anyone attentive by increasing their operating sound level (16). By spotting microphones at critical places and periodically comparing sound level to a standard, one can record the change from previous readings. If a previous correlation has been established, the part can be replaced with one that does not complain of poor health. Such provision can be designed into the equipment to improve reliability.

2.3.3 Other Indicators: Similarly the design engineer should consider whether substantial reliability improvement can be achieved by monitoring pressure, humidity, vibration, etc. Even time monitoring, for wearout failure rate characteristics, can be very useful.

2.4 COMPONENT INTEGRATION

The simplification techniques, such as value engineering, achieve higher reliability via simplification using readily available components and materials. Component integration, a close cousin, does it by deliberate multiple use of common pieces in such a way that the number of mechanical and chemical interfaces is greatly reduced.

Electronics: The prime example of such reliability improvement is integrated circuits wherein transistors, diodes, resistors, and capacitors are all plated or evaporated onto an insulating substrate, drastically reducing the number of soldered or welded connections. The following is from reference (17):

The military effect on the progress of integrated circuits has been twofold. First, new technology has developed, some through the direct subsidy of military research and development, and much more through the company-sponsored research stimulated by this support. About $100 million of R & D expenditures escalated from an initial Government expenditure of $2 million. The second effect has been the military agencies' interest not only in using integrated circuits but also in providing the market and the motivation for suppliers to complete the development and establish the production capability to supply this waiting market.

Military and space applications accounted for essentially the entire integrated circuits market last year, and will use over 95 percent of the integrated circuits produced this year. Even in 1970, these applications may well be using as high a proportion as 55 percent of the circuits produced.

The "Dick Tracy wrist television set" characteristics of integrated circuits are widely known, and there are tremendous size and weight reductions in electronic equipment using these techniques. In many applications, particularly those in which weight is critical, these reductions are very important. This is not the only attribute, however, that motivated military agencies to use integrated circuits.

Reliability is the most important single factor. We have data on two operating medium-sized computers that use integrated circuits. The first is the Apollo guidance computer, designed by MIT and built by Raytheon. It has accumulated 19 million operating hours on its integrated circuits, in which time two failures have occurred -- an initial failure, and the other a failure, external to the package, that was caused by moving the computer.

The second system, the MAGIC I, an airborne computer built by the AC Spark Plug Computer Division, has accumulated 15-1/4 million hours with two failures. Fairchild's in-house life-test program, with 33 million total operating hours, has had a total of eight failures; of these, five accumulated during the first 6-2/3 million hours and only three occurred on more recent units during the last 26-1/3 million hours.

These data are not extrapolated from accelerated tests, but are actual, observed operational failure rates, and include early production units in some cases. Considering the complexity of the function performed by these circuits, the integrated circuit equipment today is ten times more reliable than its discrete component counterpart. As new failure modes are identified and eliminated, we may see substantial improvements in the reliability figures. Extensive studies of this area is underway.

Today's integrated circuit, with minor exceptions, is just as sensitive to nuclear radiation environments as were yesterday's transistor equivalents. In some military and space applications, this will place a serious limitation on integrated circuits that use conventional transistors for the active elements.

The most liberal way to measure integrated circuit cost is to neglect development expenditures and to consider the total mission -- which includes initial cost, maintenance and repair, spare parts, logistics, and delivery. For satellite applications, with their premium on weight, integrated circuits are cheaper to use than conventional circuits.

Prices of individual transistors supplied to military contractors range from $3 to $5 in small quantity. In quantities of 50,000 or more, unit prices vary from 75 cents to $2, depending upon transistor type. Tight screening and burn-in for higher reliability will increase these prices.

By comparison, if we consider only the transistors in an integrated circuit, typical prices are about $4 per transistor in small quantities; and in quantitites of over 50,000 prices of $1.50 to $1.75 are average. The reason for this lower cost is that the silicon chip size of a typical 12-transistor circuit can be smaller than that for the 2N1613 transistor.

Performance is another factor, and there are large areas of electric equipment that cannot be equipped with integrated circuits. In general, the same limitations apply to integrated circuits and transistors. For example, we cannot replace the magnetron in the radar set, and it is difficult to make accurately tuned circuits in integrated form. However, many of the integrated circuit limitations are being overcome rapidly.

In developing any new technology, schedule slippages are expected. The electronic industry has a bad reputation in this area. There are many cases where component manufacturers have committed themselves to a delivery schedule for integrated circuits and have not met the deadline.

But as the range of circuits available as off-the-shelf items is expanded, the designers and manufacturers for the military market will find standard components much more compatible with requirements. And as the components industry gains experience with integrated circuits of special design, manufacturing and delivery schedules will be met on time.

Integrated circuits now satisfy many of the military and space requirements and there will be an increasing use of integrated circuits in military systems. Today, the advanced Minuteman, Apollo, Phoenix, and all new military digital computers use integrated circuits for the major part of their electronics systems. With higher reliability, lower cost, and better performance, many missions once considered too imaginative have become or are becoming both feasible and practical.

Hydraulic Systems: Roughly the same principles have been used for many years for automatic transmissions and servos, where the multiplicity of cylinders, valves, pipes and connections are replaced by a common casting and far fewer parts. Order of magnitude reduction in the mechanical and chemical (corrosion) interfaces provides significant reliability improvement.

Mechanical & Structural Design: The design engineer should look for component integration opportunities via casting, forging, molding, plating, etc. Since the objective is reliability improvement and/or total cost reduction, rather than just traditional manufacturing cost reduction, the design engineer must re-evaluate old rules of thumb for such decisions.

2.5 REDUNDANCY

Redundancy is the provision of more than one way to accomplish a function to protect against failure of the primary means. We often hear statements like "Never use redundancy except as a last resort" or "Redundancy is poor design", etc. While such statements are sometimes correct, usually they are not. There are many design situations where deliberate redundancy provides better reliability improvement with a total cost reduction.

There is considerable lack of appreciation by design engineers of the many ways in which redundancy can be introduced. If a particular critical part has low reliability, it does not necessarily follow that backup of that part is the most cost-effective way to compensate. Let's review the various approaches.

for which some detailed analyses are given in Chapter 5.

2.5.1 Functional Redundancy: Whenever it is feasible to satisfy a required total function via multiple components of smaller capacity, such redundancy of the smaller components may get much higher reliability without significantly increasing total cost or weight. Considerations of flexibility of operation, consumability, or sheer feasibility of capacity, often lead to the same conclusion.

Examples of functional redundancy are (a) a task force of ships instead of one very large ship; (b) copilot, to take over both jobs in emergency; (c) the shared-load fire control system shown in Figure 13-34. The analysis (1) of such a fire control system shows that the greatest Availability (A) improvement per unit Acquisition Cost is obtainable in the radar.

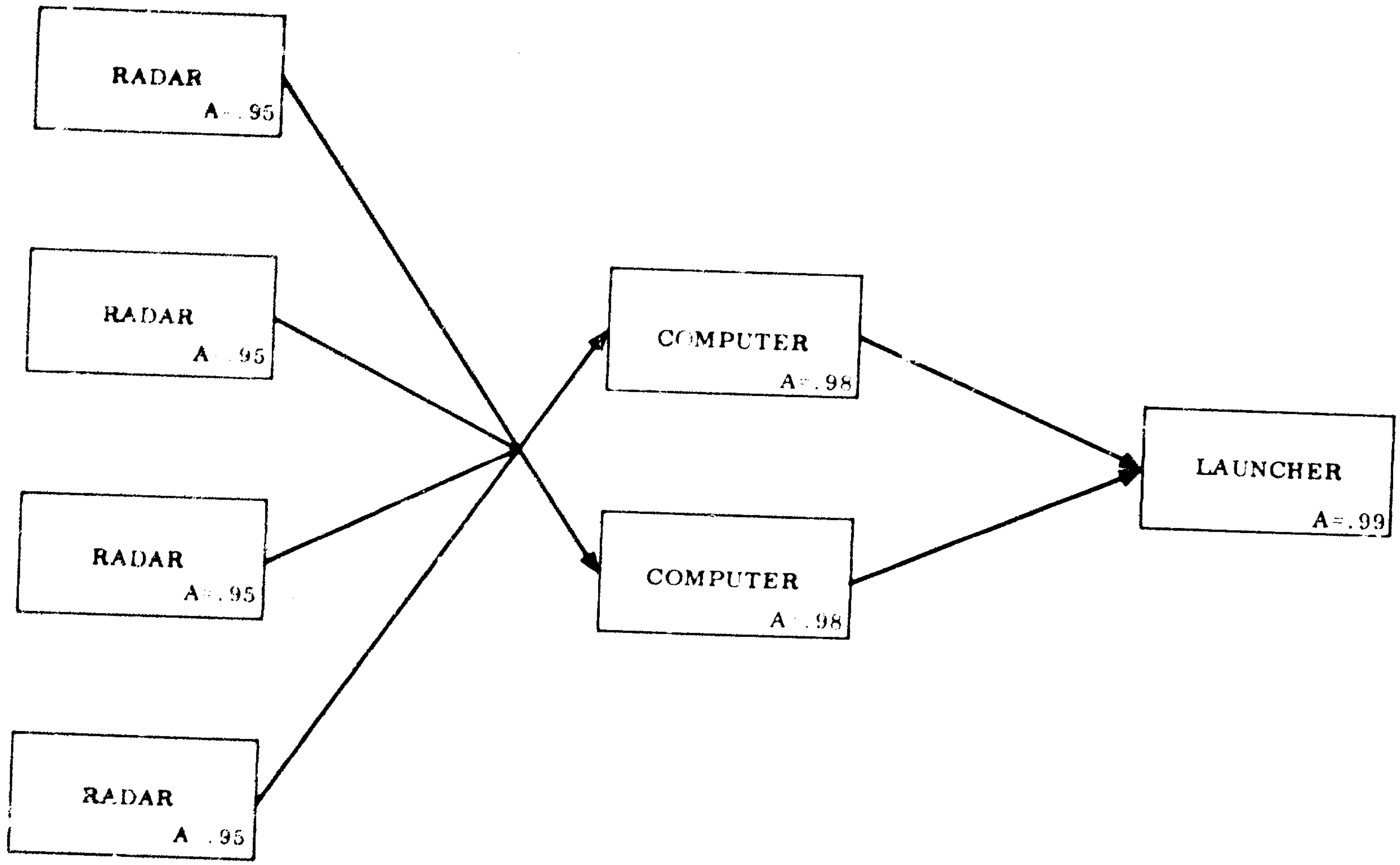
2.5.2 Operational Mode: Many operational systems involve subsystems needed to perform different functions, but which can pinchhit for each other, perhaps with reduced performance. An example is radar and optical range and direction finding equipment (18). They are each best for certain applications, but can be used as backup for each other for limited ranges. At a higher level one kind of ship can back up another in case of failure or damage. At a lower level a double-reduction gear may be provided (19) to connect the ships gas turbine generator for direct mechanical emergency propulsion.

2.5.3 Override: One man can monitor the action of many components and, if they are designed for this capability, he can "override" or compensate for component failure. This form of redundancy is so extremely common that we may not so recognize it. Examples are automatic pilot overrides, power steering mechanical override. Even competent management provides such override redundancy to compensate for subordinate failure. Less common is provision of automatic mechanical, rather than human, override. But all possibilities should be weighed.

2.5.4 Stressed Redundancy: When a particular component (or part, subsystem, or system) is known to be relatively unreliable, and no better component is obtainable for the required function, the design engineer may consider using two components in such a way that they are both operating, and therefore stressed. Often it is called "parallel" redundancy, but this term gets confused with parallel-vs-series configuration.

Thus two pumps may be operated in parallel, either one of which

FUNCTIONAL REDUNDANCY



can handle the load. Or two normally-open valves in series, where shut-off capability must be assured. Or four resistors in series-parallel or in "quad". Such redundancy obviously adds weight and cost, and cannot provide the reliability gains achievable thru Sequential Redundancy described below, but has the distinct advantage of avoiding the potential unreliability of automatic or manual switching to "spares".

In a broad sense, stress strength design (section 2.4) to a high reliability margin, involving design using more material than is necessary to handle the average stress, is a form of stressed redundancy. But the design engineer must realize that it is only one of many such redundancy alternatives, and select the most cost-effective.

2.5.5 Sequential Redundancy is the provision of spare components in such a way that they are not stressed until place into service, so that longer effective life can be expected. Often this is called "standby" redundancy, which too easily gets confused with standby modes of operation in which many components, sometimes all, are stressed.

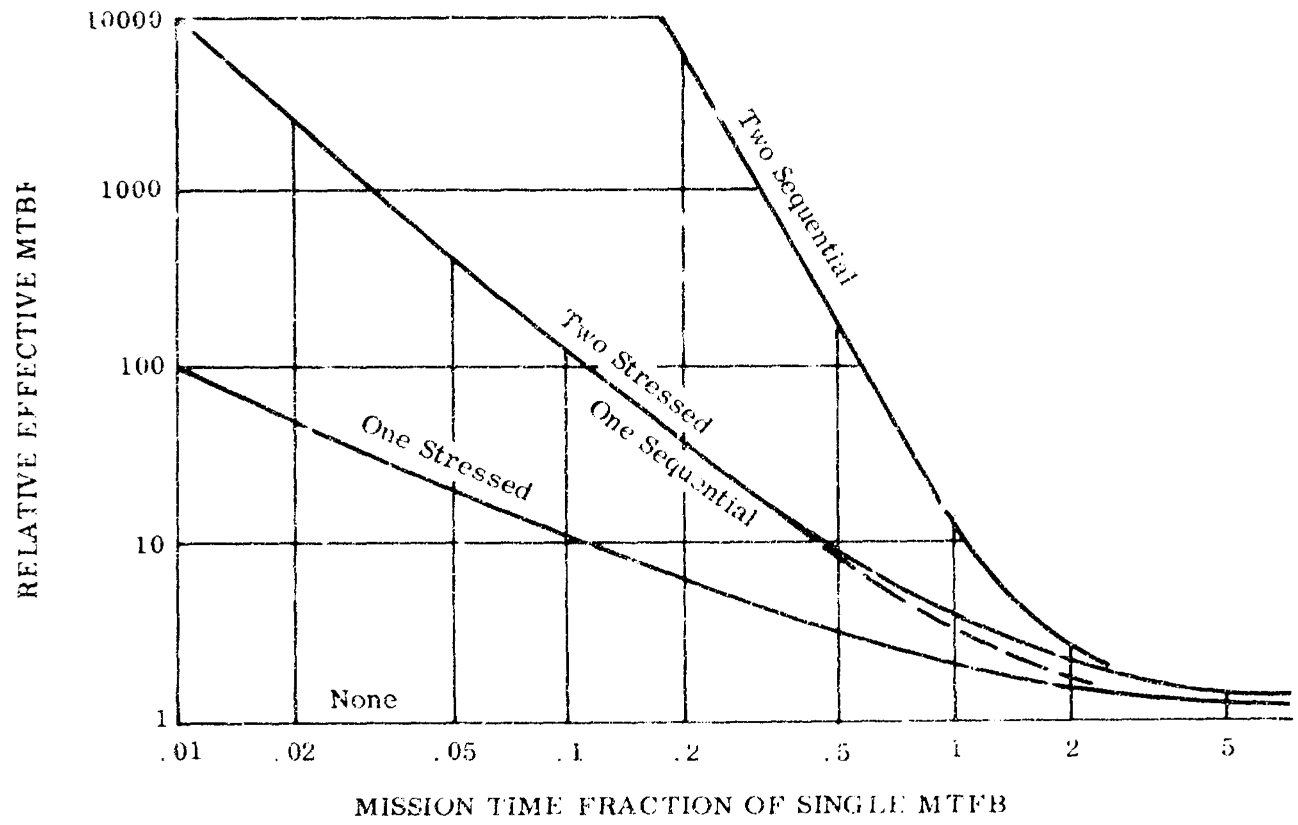
The effective reliability gain, assuming instant switching with 100% reliability, can be significant (20) as shown in Figure 13-36. Note that the potential gain deteriorates as mission time approaches the single-component MTBF. And switching is never instant nor 100% reliable.

Examples of sequential redundancy are legion. Standby pumps are commonly provided, not in operation, to back up the operating pump. Critical radio receivers are often backed up with duplicate receivers automatically switched on when output (noise or signal) fails. Airport tower operators are backed up with spare operators who only follow the action.

In the broad sense corrective maintenance is actually sequential redundancy, with much longer time constants, and may be analysed with the same techniques. But again it is the design engineers job to determine what balance of such redundancy alternatives is the most effective.

2.5.6 Redundancy Level: While not a "kind" of redundancy, the level at which redundancy is used has much impact upon the weight, cost, and feasibility of achieving a given high reliability. Consider a critical small part whose failure rate is 1000 failures per million hours. Since it is critical, it contributes $1000/10^6$ hours to the failure rate of the component of which it

EFFECTIVE MTBF GAIN



is a part, and to the next level subsystem, system, and operational system failure rates. Design action to mitigate or compensate for it can be taken at any level. And sometimes it is much easier or more cost-effective to compensate at some other level.

Moreover the effective MTBF is vitally affected by the number of "modules" into which the system can be divided, assuming a given number of "spares" is ready for each of all modules (21). Figure 13-38 shows that lower-level redundancy (more modules) is more effective, but not necessarily the most economical. One can divide the relative MTBF values by number of spares (say 70/5 = 14, or 25/3 = 8.3) to see that order of magnitude reliability improvement per "spare" is achievable.

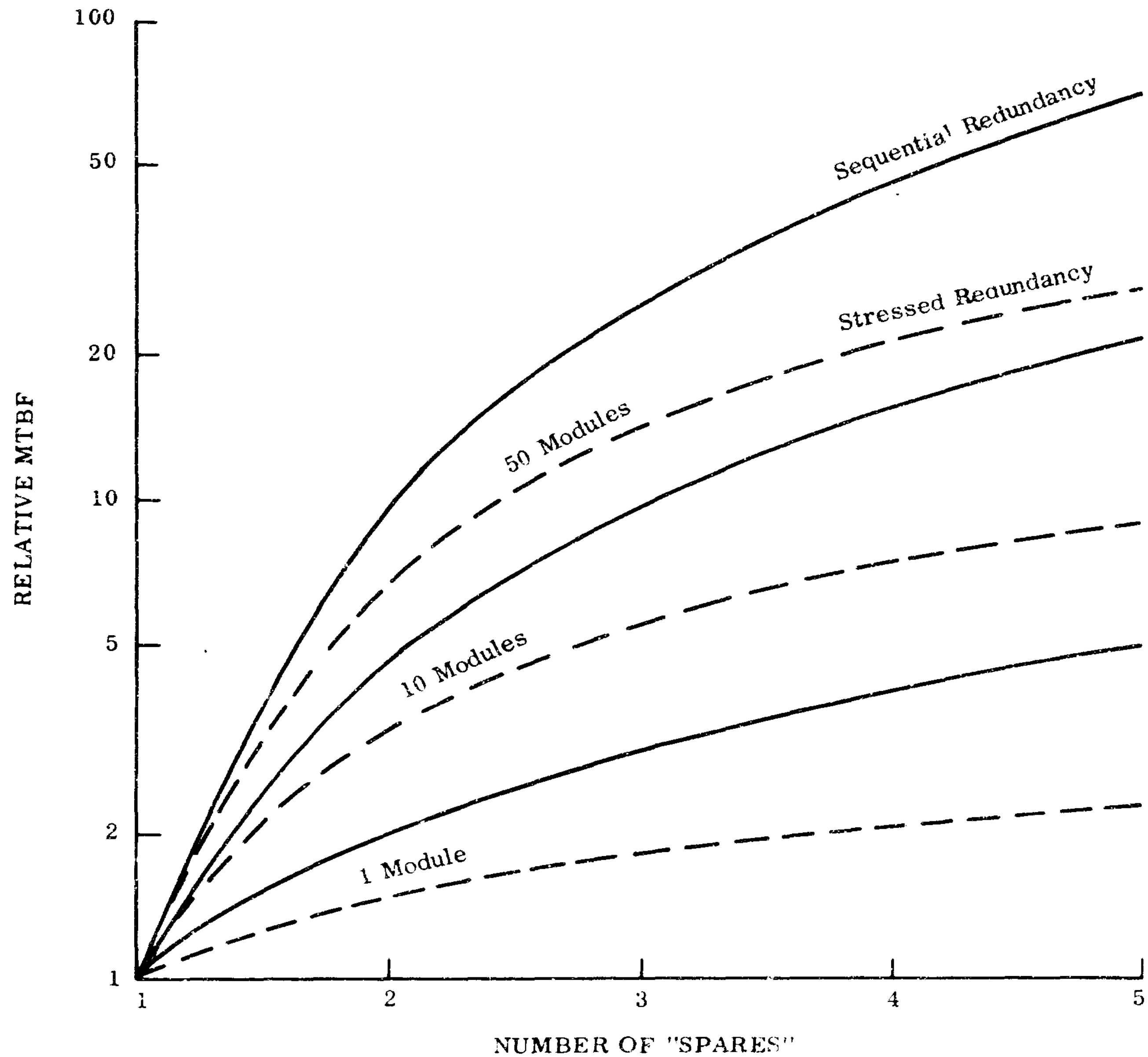
Often redundancy is achieved at the system level, such as the multiplexing of two large computers (22), or backup of a vehicle with another complete vehicle. For complex systems it is then often found that the automatic switching systems become so complex (and design is unproven) that their poor reliability prevents significant improvement of overall reliability.

2.5.7 <u>Parts Redundancy Configuration:</u> Hundreds of references are available analysing the reliability of parallel, series, series-parallel, quad, and other configurations, for "open" and "short" circuit. Many such arrangements are commonly used in design, the "quad" being favored recently (23). The same principles apply to higher levels, but then complexity makes them difficult to apply. Such analyses will be found in Chapter 5.

The quad configuration uses four components in series parallel, as in the example in Chapter 5, Figure 5-28. If the component were a valve, failure of one valve in the "short" mode (failure to stop the flow when required) would not cause system failure, since the other three would effectively stop the flow. Likewise failure of one valve in the "open" mode (failure to permit flow) would not cause system failure since the opening of the other three valves would permit flow. The quad combination, so used, protects against single failure in either mode.

2.5.8 <u>Consequences of Redundancy:</u> The major disadvantages of using redundancy to solve a reliability problem are weight, cost and complexity. Usually, (but not always) providing back up systems, parts or components adds the weight and cost of the added components. Usually the added weight and cost is reduced by application of the redundancy to the smaller sub-categories of the systems (parts rather than assembly). A more insidious

REDUNDANCY LEVEL



effect may be increased complexity, which may easily negate in some instances the reliability improvement sought. For example, where a back-up system or component is energized upon the failure of the primary, the addition of sensing and activation circuitry or mechanism may reduce the overall reliability below the reliability of the primary system.

Again, where duplication of equipment is provided to improve reliability, the cost of corrective maintenance is not necessarily changed. The cost of preventive maintenance may be essentially doubled.

2.6 PARTS IMPROVEMENT

Once it seemed obvious that since system failures are caused by parts failures, then the logical course would be to make the parts more reliable. Several years and $?0 million later we get the MTBF of only a dozen or so Minuteman electronic parts up by an order of magnitude. As General James R. Bridges said (24), "I seriously doubt that we will ever fully meet reliability requirements for space systems via the route of conventional electronic parts improvement".

If the MTBF of <u>all</u> parts of a component could be raised by 10-to-1 (at great cost) so would the component MTBF be improved 10-to-1. But many applications demand 100-to-1 or even 1000-to-1 to become adequately effective.

But it is one very important method of achieving higher reliability. The Minuteman parts program involves elaborate tolerance control, unprecedented engineering and manufacturing controls, extensive and costly testing and documentation programs, detailed traceability identification, and special packaging and handling procedures.

The contractors design engineer must therefore look for opportunities for specific parts improvement achievable at reasonable cost, or where the Minuteman cost levels may be justifiable.

3. MAINTAINABILITY DESIGN

Like reliability, the quantitative amount o[illegible] [illegible]ainability needed in a design is determined by cost-effectiveness tradeoff analyses. Once it is determined that the equipment must be restorable to operation within a given average or maximum time, the problem then is how to design to achieve it. There are at least eleven approaches that may be taken depending upon the specific circumstances, and further details are given in Chapter 8. (See Reference 25).

3.1 SIMPLIFICATION

Simpler design are nearly always easier to maintain with lesser skills in less time. See section 2.1.

3.2 STANDARDIZED DESIGN

As discussed section 2.2 of this chapter, standardization adds to the experience with a specific design and its maintainability, thus contributing to maintainability. Interchangeability further improves maintainability.

3.3 MODULAR DESIGN

Design in sets of standard subassemblies or modules permits rapid standardized diagnosis and replacement thereof, so that operation can proceed while corrective maintenance is done on the bench. Or the module may be designed for discard upon failure. On the other hand modular design usually adds electrical or other connections, which degrades reliability and adds acquisition cost, so a tradeoff analysis is necessary.

3.4 ADJUSTMENTS

A design with the fewest possible needs for adjustment, alignment, or calibration improves maintainability by reducing the required restoration time and skill level.

3.5 FAILURE EFFECT PROVISION

Basic to all design for maintainability is the detailed study of failure modes (conducted for reliability design and analysis) and careful provision for maintenance resulting from such failure effects.

3.6 ACCESSIBILITY

The word is often considered synonymous with Maintainability, but is only one indispensable contributor. Obviously "human engineering" principles must be used to provide good accessibility to critical components that may fail. Perhaps the commonest deficiency is design, so that one or more other components must be removed to get at the one that failed.

3.7 SAFETY

Maintainability is improved by designing so that inadvertent damage to one component cannot occur while working on another, or by improper installation. A connector must only fit its mate, among those handy.

3.8 EVALUATION TESTS

Just as for reliability, many situations cannot be evaluated adequately via paper design and analysis. If the component maintainability is critical (failure to restore in time fails the mission) then mockup tests are imperative, with appropriate design to resolve the problems thus brought to light. Fortunately such tests are much easier and less costly than reliability evaluation tests.

3.9 IDENTIFICATION

Much downtime is contributed by inadequate identification of original components and their replacements, particularly when replacements come from different suppliers, with a different number, and look different.

3.10 TOTAL MAINTENANCE POLICY

The restoration time for any one component is of course dependent upon logistic availability of a replacement or tools to repair, and upon adequate skill availability. Conversely the total system maintainability depends upon the integrated summation (not arithmetic) of all component maintainabilities. Thus maximum system maintainability can be achieved only by considering all tradeoffs and establishing a total maintenance policy for the system design, but consistent with available or achievable maintenance resources.

3.11 FAILURE DETECTION & ISOLATION DEVICES

Many systems and components can fail in such a manner that the failure is not apparent until a later time when its consequences show up. Computers can thus make costly mistakes. An oil port to one bearing can become clogged. Thus maintainability of such systems can be helped by adding critical failure detection devices, such as computer check routines, or limit-contact thermometers for bearings. For complex systems such devices to catch part failures would be prohibitively expensive, so the detection is done at higher levels. But this introduces the need for failure isolation devices which, once a failure is known to have occurred, help to locate it precisely. These all contribute to design maintainability.

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Chapter 14

HUMAN FACTORS

Chapter 14

HUMAN FACTORS

A basic assumption of the system development point of view is that man can be considered as one of the major components of a total system. This view is opposed to the notion that man simply plans, buys, develops, and uses a system once it is built. Any reasonably complex system requires a true interaction between man and the other parts of the system, which may be machines, other men, or combinations of these. Some way must therefore be found for thinking about the functions of machines and the functions of men within a framework which makes possible the relation of these two kinds of functions to common goals -- that is, to system goals. Even in a system as familiar and as relatively simple as the automobile, it is easy to see that the goal of transporting passengers over roads requires not only the functions of the machine itself but also a considerable variety of human functions performed by the operator, as well as auxiliary functions performed by such people as traffic policemen and filling-station attendants. The design of a system which is to be successful in achieving some socially defined purpose requires thorough and continued consideration of the interacting functions of both men and machines.

In this chapter we will attempt to develop three basic areas. (a) The proper use of man in the system, based on his capabilities and deficiencies; (b) The unknown, but potent, effect on the reliability of the system of using man as a subsystem or component; (c) Methods of integrating man into the system.

The "Human Engineering" aspects of human factors, dealing with design of hardware for compatibility with people, is not covered in this chapter. The criteria for design and analysis of such "operability" and (human) "maintainability" will be found in chapter 8, since it is often associated with hardware maintainability. But the identical principles apply to design for operability. Chapter 8 also references the principal handbooks on Human Engineering, which has a very significant impact on reliability, but is beyond the scope of this course.

1. MAN AS AN ELEMENT

What we propose to do in this chapter is to describe some of the functions of man and to show how these can be related to the functions of the machine environment in which man is placed as part of a system. We shall attempt to do this by developing and using a language that relates input for the human being to his output, which in turn becomes an input to some other portion of the system. In other words, in dealing with man's functions, we shall be identifying the kinds of transformation which an input undergoes in order to be reflected as a human output.

1.1 PURPOSE OF MAN IN THE SYSTEM

A system is developed to fulfill some human purpose or intended use. Its purpose may be to protect against enemy military attack or to harass or destroy an enemy in wartime. But systems, of course, are not confined to military enterprises. They may have distinctly civilian social purposes, such as those of an airport-to-city transportation system, a mail-sorting system, a check-cashing system. Any system is defined in terms of its purpose.

In order to fulfill a purpose, a system must meet certain standards. System developers have been known to take the point of view that if only the hardware subsystem can be made to run (perhaps in a specially prepared test location), somehow human beings with the proper characteristics will be found and "fitted into" the system. Such a view places too much dependence on the range of human talents and on the availability of suitable manpower, as well as on the extent of human adaptability. On many occasions this restricted view of systems, and system development has led to failures, breakdowns, costly programs of retrofitting, and even to virtual system abandonment. No system is complete until it can be shown to operate within a total setting that includes human beings; no system can truly be said to be successful until its operational effectiveness is demonstrated. The best system development is that which includes consideration of system operation (rather than merely hardware operability) from the very beginning of system design.

In one concept the human operator is pictured as a "data transmission and processing" link inserted between the displays and controls of a machine. An input is transformed by certain mechanisms into a signal, which is displayed as a pointer reading, a pattern of lights, an oscilloscope wave form, or the like. This information is read by the human operator and transformed into responses -- the pushing of switches, the moving of control handles, and so on. These in turn generate control signals which are transformed by mechanisms into system outputs.

Man's functioning enters into complex systems at many points and in many particular ways. Furthermore, the display of information, the controls to which the individual responds, and the mechanisms which provide the transformations for these components of the system are of considerable variety. Accordingly, we need to recognize at once that the generalized picture, while it indicates man's position as a system component, does not provide the means for a detailed analysis of the variety of human functions. It would be a mistake to think that because man typically "occupies a space" between machine displays and controls, his functioning can be related in a constant set of ways to such inputs and outputs. The fact is, neither the input nor the output by themselves will tell us the nature of man's functioning. For there are different kinds of transformations which may be performed (by the human nervous system) in turning inputs into outputs.

1.2 FUNCTIONS PERFORMED

Suppose that a system has available an oscilloscope as a basic unit for display. On the face of this scope appears a 60-cycle wave form which can be adjusted in amplitude to a particular size, the required size being given by two fine horizontal lines on a transparent overlay placed against the tube face. Let us assume that the system requires the amplitude of the wave to be determined within very close tolerances before further operation of the system can take place. Following this, what happens is that an external signal distorts the form of the wave, and it is the human operator's task to "report" the nature of these distortions by pushing one of five buttons. If there is an amplitude distortion (vertical displacement from the overlay markers), he pushes button 1; if there is a frequency distortion (horizontal displacement from other markers), he pushes button 2; if there are additional frequencies present (irregular wave pattern), he pushes button 3; and so on.

Now, saving certain details for later consideration, let us consider the difference between what the operator does in "getting the equipment ready to operate" and what he does in "operating." Actually, he is utilizing two different functions in the two cases, even though the display may be the same in both.

In placing the equipment into proper operating condition, the human operator is making use of the function of <u>sensing</u>. That is to say, he is using his visual receptors, nervous system, and effectors simply to "report" (to a machine, typically) the presence or absence of a difference in physical energy. In this case, the physical difference being reported is the coincidence of two points (or small areas) each of which lies along a narrow band of light (a "line") which makes an abrupt gradient of intensity with its surroundings. The operator is exercising a function called visual acuity, a particular name for one of his sensing functions.

It may be noted, however, that the operator is able to do much more than this, even within the equipment-readying stage of operation we are considering. He is perfectly capable, for example, of making an output which reports the amplitude of the wave along some scale such as millimeters or volts. He is able to tell us the color of the wave form, to estimate whether it is bright enough, or whether it has a regular appearance, and many other things. Why does he not do all these things in this situation? There is no mystery to this question at all: he does not simply because we have not told him to (or perhaps told him not to). But this means we must recognize that there is more to the matter of input than simply the presence of a display. In order to get the output required by the system, the operator must be provided with a set of instructions.

One basic purpose of these instructions, we are now able to see, is to determine which functions "higher up" than sensing are to be shunted out. The combination of the oscilloscope display and the instructions is what determines the output that will be made. The instructions say to the operator, in effect: "Report coincidence between a set of lines. Do not report their shape, or size, or brightness, or regularity, or meaning, or anything else." Thus, it is apparent that the effect of presentation of the oscilloscope display plus a particular set of instructions is to put into operation a particular kind of human function, sensing, and to shunt out other kinds of functions of which the human operator is capable.

Now let us contrast this elementary kind of behavior with what occurs when the equipment is being operated rather than merely turned on. In this case the human operator must function in quite a different way. He must provide five different output responses (press one of five buttons) whenever a particular kind of deformation of the sine wave appears, whether it is a change in the horizontal dimension produced by variation in frequency, in the vertical dimension (amplitude), or in one of several other types. In other words he must identify five different classes of patterns appearing on the scope.

When the operator is engaged in this function of identifying, has the internal mechanism for sensing been shunted out? Of course it has not, because the physical differences which determine the existence of classes of stimuli to which the operator responds must be sensed in order for identification to take place. Thus we see that, on the input end, human functions have a hierarchical arrangement. The use of a function like identifying requires that a function lower in the hierarchy, sensing, be put in operation as well.

Again, however, we can see that certain even higher functions have indeed been shunted out when we ask for identification. For example, the operator may be capable of telling us that a deformation of the sine wave in the vertical dimension "means" a change in amplitude. But we have not asked him that; we merely asked him to press a button indicating the presence of a particular class of change in wave shape. Or again, he may be capable of interpreting this kind of change as indicating the presence of a type of remote signal received at the other end of the system. Again we see that one of the primary effects of instructions is to keep the human being functioning at the proper level and to shunt out other, higher-level functions.

Another internal mechanism must be added at this level, too, and that is memory. For we know that without some kind of long-term storage of representations of the five different changes in wave shapes, the achievement of five different outputs would be impossible. Instructions alone will not do the job. To be sure, we can describe to the individual what he is expected to do, by means of instructions, but he will nevertheless not be able to do it by this means alone. He must have an internal means of matching the external display to one of five classes in order that he can make five different responses, as required in our example. This means he must have previously acquired the "representative shapes" in his memory, by means of learning preceding the occasion when he tackles the job of operating his equipment. And this provides the basic reason for training, as well as for the crucial part it plays in the system development process.

Now, this description of two examples of human functioning has not involved very high-powered psychology; we are well aware of that. We have, in fact, been describing the functions of sensing the perceiving, which have been studies by psychologists for many years. But the purpose of our account has not been to review basic principles. Rather, it has been to show that the fundamental operations in describing the functions of a man's behavior are the operations of a design engineer in describing a machine. Psychologists make the same kinds of inferences about human behavior as designers do of machines, and they are based upon the same kinds of objectively defined operations. It should therefore be quite easy for the designer to understand the nature of human functions, provided he learns what input conditions must be met and what the output achieves (as an input to the next unit of the system). In our further delineation of human functions, we shall find it useful to refer back to the conceptions developed in these relatively simple examples.

1.3 COMPARISON OF CAPABILITIES

The relationship between men and machines may be clarified by listing some of the functions in which men surpass present day machines and some of the functions in which present day machines surpass men. Men excel in their ability to:

1. Sense or detect minimum amounts of visual or acoustic energy
2. Perceive patterns of light, sound, or odors
3. Improvise and use flexible procedures
4. Store large amounts of information over long periods and to recall relevant facts at appropriate times
5. Reason inductively, and
6. Exercise judgment

Machines excel in their ability to:

1. Respond rapidly to control signals
2. Apply great force smoothly and precisely
3. Perform repetitive routine tasks reliability
4. Store information briefly and erase completely
5. Reason deductively, including ability for computation, and
6. Handle highly complex operations--many tasks at once

This summary of the functional superiorities of both men and machines perhaps indicates why there is a growing belief among engineers that we should go to systems of increasing automaticity. Nevertheless, man's superiority in adapting to changing demands is one of the fundamental reasons why much can be gained from including human elements in a system. It appears likely that for the predictable future the human being will continue to be an integral part of all mechanical or electronics systems, in their operation and maintenance. Therefore it is important that sound decisions be made about his duties--what they should be and how they should be performed. (Figure 14-8)

We use the term computer in a general sense to identify machines that accept signals or data and take specific action programmed

LIMITATIONS OF FUNCTIONS

Conditions for function	Limitations: Human	Limitations: Machine
SENSING		
Display	Limited to certain ranges of energy change affecting human sense	Range extends far beyond human senses (X-rays, infrared, etc.)
	Sensitivity: very good	Sensitivity: excellent
Filtering	Easy to reprogram Difficult to control	Difficult to reprogram
IDENTIFYING		
Display	Can be varied over relatively wide range of physical dimensions	Can be varied only in very narrow range of physical dimensions
	Channel capacity: small	Channel capacity: large

into the machine. In this sense, automatic boiler feed control systems and voltage regulators are examples of computers. While the more complex computers are primarily electronic in nature, the application of human capabilities in the design is fully as pertinent in many mechanical systems.

The most important respect in which men excel computers is in the accessibility of the items in storage. Men can get at a single memory in many different ways; in particular, they can recover memories on the basis of similarity alone. Computers, by contrast, have no such efficient cross-indexing. If they did, it would be possible to write programs which rely on the computer to locate and produce any item in memory without specific instruction concerning where that item is. At present, no such procedure is possible.

A major virtue of men is that they have a high tolerance for ambiguity, vagueness, and uncertainty. Men are able to detect what other men mean though the smog of what they say, and they customarily do so and behave accordingly. Such tolerance for ambiguity is based on a life-long history of experience with ambiguity and on the ability to argue by analogy from one's own purposes to those of other people. Neither of these characteristics seem likely to be available for computers in any near future. So long as computers cannot tolerate and exploit ambiguity, they cannot be given major executive responsibilities unsupervised; social control is usually based on vague mandates which permit wide but not unlimited latitude in interpretation (for example, platforms of political parties). This means that man-machine systems will necessarily continue to have men with veto power over computer-generated decisions, rather than vice versa.

One reason why men are good at tolerating and exploiting ambiguity is that they can effectively translate uncertainty into probability--another task in which men far excel computers. Consider the statement, "Before you go to bed tonight, you will consume a bottle of beer." Presumably that statement is neither impossible nor certain. A computer could probably go no farther; a man can attach a number to the statement which represents his evaluation of its probability of being correct. Such numbers are, it turns out, excellent guides to action; men can accurately translate uncertainty into probability. Computers, on the other hand, are far superior to men in taking probabilities and pay-offs and computing from them the best course of action in accordance with rules set down by man. These considerations suggest that a military-information processing system which must cope with relatively unreliable data (such as a sonar system) might profitably use human operators as transducers for probabilities. These probabilities could be entered into a computer, which would then compute the optimal course of action in the light of them. No such system now exists, but it seems entirely possible that they might be one ten years from now.

In a very important sense men are far more reliable than computers. It has already been pointed out that computers make far fewer mistakes than men. But in general the mistakes computers make either remain unchecked or stop the computer completely. Man, on the other hand, can detect his own mistakes and spontaneously work out a plan to correct them or remedy their effects. Furthermore, once he has learned how to perform a task correctly, man does not repeat and repeat the same error, as will a computer with a broken part. In short, if a little allowance is made for the approximate nature of human reliability, man is far more reliable than any computer yet invented, or any likely to be invented in the near future.

1.4 BASIC TECHNIQUES IN DESIGN

1. Allocation of functions among men and computer should consider the best skills of each. It is seldom wise to allocate to the computer everything the designer knows how to mechanize, and to parcel out among the system operators whatever is left over.

2. If possible, the computer should be about 80 per cent used; if it has too much unused time or capacity, either a smaller computer should be used instead or tasks for which it is less than ideally suited (such as long-term memory) should be given to it. Computers do not profit from rest periods, other than the necessary halts for maintenance and repair; men do. On the other hand, tasks change, and a little flexibility is therefore desirable.

3. Provision of one sort or another must be made for system function during computer malfunction. This often implies either a second computer or a manual back-up system. In some cases, of course, no meaningful provision is possible or worthwhile.

4. Operator jobs should not be homogeneous in difficulty. Some jobs should require a relatively high level of ability and training; others should not. This reduces the requirement for high-IQ operators and provides for a career structure within the system.

5. Man-to-man communications should be carefully evaluated. In

general, human outputs should go into the computer. The process of man-to-man communication is often so clumsy and imprecise that the system is sometimes better off if two functions performed by different men are separated by a function performed by the computer. This principle is controversial; some experts insist that a great deal of informal man-to-man communication is both necessary and desirable.

6. Man should function as aids to the computer in sensing, extrapolating, and decision making. The idea of using men as back-up systems for computer functions is very widely applied; most manned space vehicle designs are designed that way. There is some question whether in many applications it might not be cheaper and just as effective to have the man perform the function in the first place.

7. If at all possible, the computer rather than a man should have primary responsibility for maintaining vigilance and detecting when, after a period of inactivity, some system action is required.

8. A number of specific tasks which must be performed in most information processing systems are usually allotted to men because they use man's best skills. The functions of detection and identification have already been discussed; they exploit human pattern-recognition ability and ability to cope with uncertainty. Another common function is goal-setting for searches. Computers very often solve problems by means of directed search through a very large set of possible solutions. Searches should usually be guided by hypotheses concerning the most fruitful places to search first.

9. Yet another important human function in computerized systems is censorship. Men monitor the output of computers, with responsibility to veto computer actions when it seems appropriate to do so. Unfortunately, as systems get more complicated and their tasks become more demanding, it will be more and more difficult for men to censor system output effectively. They cannot assimilate enough information to be sure whether the system is right or wrong, except in the case of gross malfunction. More important, systems can seldom tolerate the response of doing nothing, and men often cannot accumulate the information in time to supply alternatives to the computer's recommended course of action.

10. It will continue to be true that systems which include computers exist to serve human purposes, so system goal-setting will continue to be a human function, the most important human

function in the system. However, that function will be performed mostly by the designers of the system and those who write the computer program; the nature of system design pretty completely determines the goals which it can effectively further.

2. THE MAN-MACHINE INTERFACE

Having stated some general principles applicable to the design of human tasks, we can turn our attention to the ways in which design is actually made concrete within the system development process. It is apparent that the human operator, whether functioning as an information processor, a decision maker, or both, occupies a position as a link between two other portions of the system. This means that he: a) responds to the preceding unit's output as his input and b) by his action provides an input to the next unit. When provided by a machine, the configuration of output events that constitute input to the human operator is generally called a display. The physical objects which he operates (particularly with his hands and feet) in order to provide an input to the next unit in the chain are called controls. Obviously, the way the human operator must function within the system will be determined by the nature of these displays and controls. Accordingly, considerations of effective design for the man-machine configuration usually result in decisions concerning the physical characteristics of these aspects of equipment.

2.1 DISPLAY DESIGN

The goal of display design is to provide the operator with usable information germane to his task within the system. One can usually begin with the assumption that the system has at the outset the basic means of acquiring all the information that might conceivably be useful. But once the information is attained, how and in what manner should it be distributed among, and presented to, the human elements of the system? The problems can be defined somewhat more specifically. The variables of interest in the design of displays have been classified in the following ways:

1. Readability, legibility. Obviously the operator must be able to hear or see or in some other way sense the signals being provided for his use. He must also be able to sense differences among different signals; variables concerning both the display proper and the viewing or sensing environment (for example, illumination) come within this class.

2. Sensory modality. The question raised by this category

concerns which sensory mode should be employed to convey various kinds of information.

3. Multiparametric or combined displays. Here are included questions of what and how many different kinds of information can be incorporated within a single display and how this is to be accomplished most effectively.

4. Display coding. This category implies questions as to the language form or the kind of symbols to be employed in presenting information.

5. Filtering. Questions of this class concern ways of pre-selecting information inputs so as to simplify the interpretation task.

6. Clutter and noise. Included in this category are problems pertaining to the elimination of false or masking signals in the display.

2.2 DESIGN OF CONTROLS

The ruling concepts in control design should be order, coherence, and organization. Rather than flexibility or changeability, one wants control devices to have the properties of being orderly and consistent in their operation and action consequences. From the standpoint of the human operator, perhaps predictability may be thought of as the most desirable characteristic.

The layout of control panels and consoles is a good place to begin consideration of control design problems. The basic technique for the designer consists in analyzing the task. The task analysis provides a map of what the operator is supposed to do in carryout out his job. Traditionally, the analysis is a description of isolated actions in sequence. For relatively simple tasks (for example, mechanical assembly) the classic "therblig" of industrial engineering is appropriate. With increasing operational complexity, as well as the necessity to develop equipment for tasks which are almost entirely novel, newer techniques are needed. By whatever means obtained, however, an analytic map of the task is essential.

Just as the system as a whole may be functionally organized according to operations, the control layout can be so organized. Functional grouping, ease of access, differentiability of sub-operations, and the like then come into play as criteria for console design. Unfortunately, the criteria are not always (in the controls to which the individual responds, and the mechanisms which provide the transformations for these components of the system are of considerable variety. Accordingly, we need to recognize at once that the generalized picture, while it indicates man's position as a system component, does not provide the means for a detailed analysis of the variety of human functions. It would be a mistake to think that because man typically "occupies a space" between machine displays and controls, his functioning can be related in a constant set of ways to such inputs and outputs. The fact is, neither the input nor the output by themselves will tell us the nature of man's functioning. For there are different kinds of transformations which may be performed (by the human nervous system) in turning inputs into outputs.

1.2 FUNCTIONS PERFORMED

Suppose that a system has available an oscilloscope as a basic unit for display. On the face of this scope appears a 60-cycle wave form which can be adjusted in amplitude to a particular size, the required size being given by two fine horizontal lines on a transparent overlay placed against the tube face. Let us assume that the system requires the amplitude of the wave to be determined within very close tolerances before further operation of the system can take place. Following this, what happens is that an external signal distorts the form of the wave, and it is the human operator's task to "report" the nature of these distortions by pushing one of five buttons. If there is an amplitude distortion (vertical displacement from the overlay markers), he pushes button 1; if there is a frequency distortion (horizontal displacement from other markers), he pushes button 2; if there are additional frequencies present (irregular wave pattern), he pushes button 3; and so on.

Now, saving certain details for later consideration, let us consider the difference between what the operator does in "getting the equipment ready to operate" and what he does in "operating." Actually, he is utilizing two different functions in the two cases, even though the display may be the same in both.

In placing the equipment into proper operating condition, the human operator is making use of the function of <u>sensing</u>. That is to say, he is using his visual receptors, nervous system, and effectors simply to "report" (to a machine, typically) the presence or absence of a difference in physical energy. In this case, the physical difference being reported is the coincidence of two points (or small areas) each of which lies along a narrow band of light (a "line") which makes an abrupt gradient of

6. Display compatibility. In the total configuration of displays and controls making up the operator station, display control arrangement should be correlative; that is, controls governing the process being displayed should be in proximity to their related display. Display format and content should be dimensionally similar to control location and direction of action.

As our previous discussion has suggested, it is often not possible to follow all these rules with equal vigor. The design of controls and control layouts is, of course, a matter of practical compromise, as is true of other aspects of equipment design. Nevertheless, this set of principles represents the factors that are based on empirical findings of studies of human functioning, which can successfully be brought to bear on design decision having the aim of optimal system effectiveness.

2.3 REDUCING HUMAN ERROR

On the whole, our discussion of design problems has been carried out in the context of human functioning, and particularly in consideration of the ways of eliminating the kinds of functioning that result in error. The analysis of possibilities of operator error leads to the conclusion that its causes may often be identified as deficiencies in equipment design, whether of displays, controls, or the expected interactions between these two types of elements. The information obtained from such analyses is exhibited in summary from in Figure 14-16. It will be noted that many of these difficulties provide the possibility of correction by means of equipment design (for example, unclear code form), whereas others would appear to be avoidable by the provision of external instructions, possibly by means of job aids (for example, inappropriate filtering set). In still other instances, it appears that corrective action would take the form of training to be undertaken after the equipment configuration has been determined (for example, action-control relationships not understood by the operator).

It seems evident from the figure that there are a number of ways of preventing, minimizing, or reducing the deleterious effects of operator mistakes, when one recognizes that such errors may be understood as matters of inadequate functioning of human information-processing and decision-making activities. In many cases, the avoidance of faulty human functioning can be specifically related to the design of equipment displays and controls, and particularly to the extent to which they define sensible human tasks. If one looks beyond these principles (paragraph 2.2), he can foresee the possibility of a systematic

TYPICAL HUMAN ERRORS

Type of Error	Possible Causal Factors
Failure to detect signal	Input overload a. Too many significant signals b. Too many separate input channels Input underload a. Too little variety of signals b. Too few signals Adverse noise conditions a. Poor contrast b. High intensity of distraction stimuli
Incorrect identification of signal	Code form or typology unclear Lack of differential cues Inappropriate filtering set (expectation) Conflicting cues Conflicting identification requirements
Incorrect value-weighting or priority assignment	Nonlinear predictions required Multiple or complex value-scaling required Values poorly defined or understood Contingencies vaguely defined
Error in action selection	Matching of actual and required patterns faulty Consequence of courses of action not understood Appropriate action not available Correct action inhibited a. Cost considerations b. Procedural prohibitions
Error of commission	Correct tool or control not available Action-control relationship not understood by operator Action feedback unavailable or delayed

theory of human performance, for which currently acceptable categories of human functioning provide only the bare framework.

3. EVALUATION OF MAN IN THE SYSTEM

It has been pointed out earlier that engineering specialists utilize tests as a practical way of reducing uncertainty and providing feedback about component, subsystem, or system performance. It is a means whereby information is obtained about the validity of design decisions. It is also a way to advance the state of the art by a trial and error approach when a more rigorous scientific approach is not feasible, as in the time and cost environment surrounding development programs. The wide use of engineering test programs has also led to the development of standard tests, standard test procedures, and improved test instrumentations which permit more elegant, more pertinent, and more economical testing. For example, over 300 flight tests were run on the V2 to achieve desirable performance characteristics. The Sergeant missile, which was later developed by many of the same individuals who developed the V2, performed adequately after approximately 50 flight tests.

Testing has also uncovered facts that were not or could not be foreseen by pretest logical analyses. For example, on one program there were a number of tests which ended with the missiles breaking up in mid-air. It was only after sufficient testing that the reason for disintegration was identified as analytically unexpected torsional bending stress. As a result, current missile programs collect data on this parameter as a matter of course.

Engineering test activities, briefly, include: (a) making predictions about the performance of the system (or of some subsystem or component), these predictions being usually based upon interpolation or extrapolation of established data; (b) designing tests to confirm predictions; (c) instrumenting the test area and vehicle in order to acquire pertinent data for the evaluation of the predictions; (d) evaluating and comparing predicted performance with actual performance; and (e) employing the results of test as the basis for analysis of the discrepancies between predictions and empirical results and to modify the model from which the predictions were made, or the system, or both.

It should be pointed out that there is a difference in intent and in criteria between the type of "testing" that is involved in an engineering development program and the type of "testing" that is involved in traditional research experimentation. The engineering test program has as its primary concern the achievement of an "adequate" system where "adequate" is defined as a system that meets design objectives. In this context, one is not primarily concerned with determining "good" design or "optimum" design, or with collecting basic data, but only with the question, "Does the system meet required and predicted performance criteria?" It is assumed that the designer and design management are concerned with providing the best design possible, and that they make use of available experimental data. Thus, tests must answer the question, "Does the design, which is assumed to be the best that the designer could produce at the time the design decision was made, meet the design **requirements**?" An example in human engineering terms would be a tracking operation in which the operator is required to track two objects within certain time and accuracy limits. The human engineer would provide the "best" information he had at his disposal at the time a decision to include such an operation was required. The purpose of human engineering test, then, would be to determine whether operators do indeed perform within the specified limits, and not whether the design that was recommended turns out to be the optimum design for the circumstances under which it is finally used.

3.1 HUMAN FACTORS ENGINEERING TESTING

Performance testing and malfunction reporting attempt to provide workable ways of arriving at quantifying the effects of the man on the system. Most malfunction data collection systems are already making some attempt to obtain data on human-initiated malfunctions. Consequently, the following approach is based on modification or extension of existing malfunction data collection systems.

3.1.1 Identifying and Describing Human Performance: The achievement of adequate over-all system performance within the constraints of given dollars and time is the primary task of a system development program. However, the size and complexity of modern weapon systems make it necessary to subdivide the system and its developmental task into manageable parts upon which can be brought to bear the varied capabilities of many individuals and groups. The parts or subsystem entities that are most familiar are the equipment "packages" in the form of subsystems, components, or their smallest "bits and pieces." These provide the equipment designer with discrete entities that can be separately analyzed and designed within the context of the system as a whole, and for which performance predictions can be made and tested. Alone or in various assemblages, these hardware entities are used as the primary vehicles for test design, test data collection and analysis, and any subsequent system modifications.

From the viewpoint that man participates in weapon system functions through the operations he performs, it appears appropriate to use the operation as the entity that is the human factors engineering equivalent of the hardware designer's "black box."

3.1.2 Performance Testing: In order to develop a human factors engineering test program, a number of problems have to be considered. The approach to human factors engineering performance testing proposed here considers the following:

1. Identification and selection of critical human operations.
2. Specification of pertinent parameters of these operations.
3. Prediction of the values of these parameters.
4. Confirmation through test of predicted parameter values.
5. Adequacy of test data.
6. Test implementation.

3.1.3 Identification of Critical Human Operations: Critical operations as a subcategory of all human operations can be defined as those which, if not performed in accordance with estimated design values, will most likely have large effects on a system's performance or cost.

3.1.4 Selection of Critical Operations: For systematic consideration, the operations that humans perform in a system can be organized and presented in the form of block diagrams. Each operation must be considered and a decision made as to whether that operation is to be included for evaluation in the test program. A typical priority list would consider such factors as:

(a) Past Performance: If the man or man-machine operation is in all essential aspects similar to man or man-machine operations of previously evaluated weapon systems, this previous experience would be important in determining the necessity for including a test of the operation in the test program. Past malfunction experience can provide a useful guide in this regard.

(b) Value Loss: The estimated amount of time, accuracy, or cost penalty that may result from an operation that is performed imperfectly is another factor that must be considered in determining the test priority of that operation. The priority for inclusion in the test program is highest for these operations which have the greatest estimated time, accuracy, or cost penalty associated with them.

(c) Test and Evaluation Cost: Since the tests of man or man-machine operations are tests of components and subsystems of the over-all weapon system, tests of these components and subsystems can often be included in over-all system or subsystem tests.

3.1.5 Specification of Parameters: Once a selection has been made of the critical human operations of the weapon system that are to be subjected to performance testing, these operations must be described in an appropriate way. This means the operations parameters must be selected and specified in a way which adequately describes the operations and specifies the criteria to be applied so that the operations are measurable in test and so that they are subject to modification for system improvement.

3.1.6 Prediction of Parametric Values: After the important parameters associated with the critical operations to be tested have been specified, the values that these parameters may be expected to assume are predicted. There are few formulas available which will allow the calculation of exactly how fast or how accurately a man will perform a certain operation in a given situation.

If no formal or semiformal model of an operation is established, then a tester would be forced to take data over the entire range of each parameter and for combinations of parameters. Good test design is the art of predicting (hypothesizing) in such a manner that with a minimum of effort a maximum of critical information can be derived.

No matter what model or method is used to aid in predicting operator performance, the model or method must account for the value that a particular parameter may take under certain conditions.

3.2 CONFIRMATION OF PREDICTIONS THROUGH TESTING

Models that are used to predict operator performance can be confirmed only through tests. The need for such confirmation is inversely proportional to the confidence which can be placed in the predictive model. Thus, in evaluating a system, it would be regarded as unnecessary to prove through test the validity of

Ohm's or Boyle's Law; these relationships are well enough established to be accepted without any further confirmation. If, on the other hand, the predictive model is no more than a "guesstimate," or a statistical model with wide variances, then additional testing to confirm these predictive models will be necessary to give the user confidence in the system design.

Tests leading to the confirmation of predictions can be defined as a series of operations employed to determine the correspondence between a model which describes an existing or potential state of affairs and the actual state of affairs. A model (or theory) implies a hypothesis or a set of hypotheses.

3.2.1 Adequacy of Test Data: Confirmation of predictions is dependent upon the adequacy of test data. It will be useful therefore to discuss briefly several factors that are involved in test adequacy.

The amount and the validity of information obtained from test often rests on the sophistication that goes into designing the test. Frequently, it is sufficient to run tests under normal operating conditions. Under other circumstances, it may be more useful to "test to breakdown"; that is, to test under abnormal conditions where, for example, deliberate overloads and malfunctions are introduced. This may be necessary to determine the range within which certain operations can be performed with a specified speed or accuracy by human or other system components.

Once a major source of variance has been detected, it is likely that something positive can be done to reduce its magnitude. However, certainty about the original source of a variance measure can be approximated only by more investigation where, for example, specific significant interactions are rigorously examined and investigated.

3.2.2 Test Implementation: In the absence of a large body of experience with human factors performance test from which to draw examples, many questions arise. For example, who should do human factors testing,the human factor specialist, a human factor test technician, or regular test personnel? It seems obvious that the peculiarities of obtaining reliable data on human performance requires the attention of someone with training in experimental methods in the behaviorial sciences, particularly in psychology, yet the actual collection of data at a test site may be placed in the hands of someone with limited training in obtaining behavioral data.

3.3 EXTENSION OF CURRENT FAILURE REPORTING PROCEDURES

For malfunction data to be useful in the improvement of system performance, they must be sufficient for identifying the human factors involved in the reported failure events. By identifying these factors, the data make it possible to recreate the dynamics of the situation in which a failure has occurred and to determine, analytically or physically, what may have caused it and what steps to take to prevent its recurrence. To do this, the data concerning the individual failure must:

1. Identify the failed item.
2. Described the symptoms by which the failure was identified.
3. Provide a means for describing the dynamic interactions of personnel with the failed item, with other parts of the system and with the system's environment.
4. Provide information concerning the past experience of the individual failed item that might be pertinent to the failure event.
5. Record the skill level, or rating of the technician diagnosing the failure and making the restoration.

3.4 HUMAN RELIABILITY

The Personnel Subsystem concept emphasizes the development of human performance. Human reliability can be compared to hardware reliability in the system reliability program. Human performance, like hardware performance, must satisfy the performance requirements of the system.

In aerospace systems we are approaching an interchangeability for man similar to that which exists for hardware. From the performance aspect man has become a relatively standardized component in the system. He must function within a given range of tolerance to satisfy system requirements. Consequently, every individual or group of individuals in the system must be capable of providing the required performance. Personnel variability and interchangeability directly affect the operational capability of the system. Variability of the human component must be either minimized or have only negligible effect on system performance if the potential system capability is to be fully realized.

The previous tendencies for system development to be primarily concerned with only hardware development or with the assumption that hardware test data adequately evaluate the Personnel Subsystem have made it extremely difficult to empirically identify human errors and the effects of human variability on the system. However, some information on the amount of human error does exist. For example, the Shapero (3) Study indicated a range from 20 to 53 percent for human-initiated malfunctions. An analysis of 600 recent rocket engine Failure and Consumption Reports showed that 35% of the failure reports indicated equipment damage or malfunction directly attributable to human interaction with the equipment during maintenance, checkout, and transport. Up to 40% of all missile holds, postponements, and failures are caused by human error. The published studies involved a further analysis or reanalysis of data previously collected rather than the more positive effort to actually collect and classify Personnel Subsystem data as an integral part of the failure-data reporting system. If such an analysis can be performed by a group of individuals in retrospect, it should be equally possible to perform the analysis at the time the data is originally collected -- providing methods and techniques are adequate for identifying human initiated failure on the failure-data reports.

Confining human reliability to the effects of human performance structures the concept but does not solve the reliability problem. Human reliability is not easily predicted nor controlled. Human failure is not identical to equipment failure. People are not fixed components. After human performance has once been established human failures tend to be intermittent. Usually the individual who fails to perform a specific task at a specific time will perform the task correctly the next time. Intermittent human failure plagues the operational situation. Human performance is affected by many complex factors such as motivation, stress, and fatigue. These complex factors are difficult (but not impossible) to predict and control.

4. CONCLUSION

Although not generally recognized, the birth of the new era, symbolized by the term man-machine systems, occurred when the technologists produced the automatic tracking and fire control or gun laying radars. This was quickly followed by the second technological innovation, high speed electronics computers. With these machines we had devices which could replicate the logic process which heretofore had been the exclusive domain of man.

With the invasion by the machine into the logic process, the relative roles of man and machine have undergone a subtle but nonetheless fundamental change. No longer can we regard man as an entity apart from the system -- an entity who operates, maintains or controls the machine. Rather he is explicitly a part of the system contributing those capabilities which are uniquely his. Thus in theory at least we now have man-machine systems with the man assigned those tasks which he can do most effectively and efficiently and the machine assigned those tasks which it can do most effectively and efficiently.

Man is subject to the machine even as the machine is to him through the interactions which take place in today's complex systems. Certainly man's judgment must prevail and in a sense can be considered to control since the machine does not possess intellect. However, we must not lose sight of the fact that even this "man-only" attribute can be and is influenced to a remarkable extent today by the method of processing and manner of display of the processed data by the machine.

Within the context of our philosophical concept Human Factors Engineering is a very broad area of concern encompassing diverse disciplines in the behavioral sciences, physiology, anthropometrics and psychometrics. In an applied Engineering sense it includes the area which we refer to as Personnel Management and Training. Actually, one can conceive of the Personnel and Training people as being the producers of the man-modules for our systems. It is to them that our systems engineers look for the man in the systems. It is to them also that the systems engineers look for the descriptive specifications of the man available for incorporation into the system.

Herein lies the problem. While there is a positive effort to provide quality control in processing the product and in selection of the raw material input, the random nature of the origins of the raw material poses real difficulties. As a result, descriptive specifications are given in very broad parameters.

This situation is aggravated by our lack of real understanding as to how and why this raw material, man, functions. Neither do we have the attendant measuring systems for this functioning. We point with pride to the fine tolerances to which we can produce machine-elements. We measure them with micron exactness. Then we ask the system designer to combine them with man-elements which we describe as an average man with an 8th grade mentality. What precision! What an exquisitely defined measurement scale! -- and management says, "Give us systems effectiveness."

In order to reach the design goal we must first learn far more than we now know about how and why a man functions. We must learn how to measure the parameters which describe these functions. We must acquire the capability to describe exactly what combinations of man-functions are (or potentially are) in our available inventory together with the distributions of these functions. Until we are able to provide adequate man parameters to our systems designers, the probabilities of true systems effectiveness will continue to be quite low and high systems effectiveness will be more accidental than calculated. Low systems effectiveness, I submit, is the situation today. This is manifested in a myriad of reports (2).

These reports use such terms as "too complicated machines", "inadequate training", "above the heads of our people", "can't be maintained", etc. These, if you will, are symptoms. These demonstrate our inability to fit the available man-modules to the system. In almost every case, we are able to provide a combination of man-modules and machine-modules that does function effectively. More often than not we ascribe the difference between the successes and failures to such things as leadership, luck or, in some cases, a unique set of circumstances. In any case, one effective system case is evidence that the system can work effectively.

Quantizing the man function then becomes the core problem to our systems effectiveness effort. What do we do about the Man Parameters in System Support? To me, the solution is quite clear. First, management and -- explicitly Armed Forces Management -- must admit to not being the fount of knowledge in the appraisal and evaluation of the man-function.

If we are to resolve the problem, we must undertake a program of study and analysis of the man parameters in systems far greater than that which we currently have underway. We must close the gap in our understanding and measurement of the man-parameters. We must initiate and support efforts in scientific study which will lead to an understanding and measurement of the man akin to that we possess for the gear, the electron or red fuming nitric acid.

To this end, a number of projects are underway in the Navy. In an attempt to resolve the problem, the Bureau of Ships supported by the Office of Naval Material has initiated a project called TRIM. TRIM is an acronym for Training Requirements Information Management. TRIM is a systematic approach to the codification, recording and collection of training requirements data and personnel resource data in terms of training. Perhaps the most significant aspect of TRIM is that its design concept takes into account the gross nature of existing measures of man parameters. As a result the matrices in the system have been designed to provide for ultimately mor refined measures without necessitatin: a new data system.

A second Navy project, which I'd like to cite, is the effort under the sponsorship of the Chief of Naval Personnel referred to as the New Developments Human Factors Program. This is a rather broad-gauged effort to define the problem and provide solution: in the personnel management and training, or if you will, production processes for our man-modules.

However, the vast bulk of our military systems must use the so-called average man. Further, highly specialized and very expensive artificial environments are simply not economically feasible for them.

Therefore, we must learn more about how and why this average man performs. We must learn how to measure and predict this performance. These measures and these predictions may then be used by the system designer as the descriptive parameters of the man in the system. The.. and only then can we hope to achieve overall systems effe-tiveness in our military systems.

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Chapter 15

DESIGN REVIEW

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DESIGN REVIEW

The objective of design review is mature design the first time. We are trying to accelerate the brainchild's growth and learning rate, and to know when and whether it can reliably stand on its own feet.

We want to help the design engineer to "think of everything." While this may be humanly impossible when he is young, working alone or without discipline, we can come very close to "everything" with systematic assistance and guidance.

We also want to make sure that the very best available brains are applied to the design. By brains we mean both competence and experience. Most engineers realize that they do not know everything about their area of design. The very fact that they are designing implies the need to create new and untried things. But young engineers often cannot appreciate what they do not yet know. So we must find ways to make the knowledge of experienced engineers not only handily available to the design engineer, but also invariably and systematically used.

Also it is desirable to subject the design to the different viewpoints arising from experience in different fields or disciplines. An expert in one field can repeatedly miss a flaw that is obvious to the expert in another.

Achievement of this objective will of course protect the Bureau and fleet from the cost and delay of preventable errors, protect the contractor from much Bureau unhappiness, and protect the contractors community from degenerate employment resulting from consequent loss of business.

The manner in which design reviews are conducted differs mainly in degree of formalization. A conversation between a designer and a friend in another code may very well accomplish the main purpose of a design review. On the other hand requiring that an engineer complete detailed design review questionnaires solely to justify his design decisions does not usually accomplish any purpose. Formality should probably be confined to formal requirements of scheduled events (review, report, follow-up) and content of the reviews but not extended to format for those events.

It must be remembered that a design review deals with people as well as with an inanimate product. A review is not an inquisition and is, in fact, nearly always best conducted as a presentation by the responsible engineers to the review group. Many contractors have found that good engineers welcome it as an opportunity to demonstrate capability before their peers and contemporaries.

1. PHASES OF DESIGN REVIEW

Four phases of design review are readily identifiable.

1.1 CONCEPTUAL PHASE OF DESIGN

During conceptual design, the designer will want to take advantage of all of the previous experience and information that he can possibly make available to himself. Some of the types of information that he will want to consider are (a) what is the experience of similar equipment; (b) the failure reports on unsatisfactory conditions of similar designs; and (c) test information and technical engineering papers reporting on experience of other designers even to the extent of examining designs in other industries.

During this phase, numbers of different ideas are generated, modified, and discarded for various reasons. They should be studied in a series of successive approximations before one is selected for detailing. Many times after extensive layout and initial detailing is started, or even when complete, a deficiency will be uncovered which requires throwing the whole idea out and starting over. Sometimes a further look at one of the early ideas previously discarded will offer a solution for final design. It is here that system modeling techniques are of greatest value. The more complete the technical evaluation at the conceptual stage, the more probable that time will ultimately be saved, and the design will survive. Initial dependability requirements are established and apportioned for compliance at this stage.

Once the designer has gathered all of his information described above, he will want to review it prior to proceeding on to the next phase of design. To most effectively accomplish this, he will need to hold a discussion with many participants from whom he has gathered the information during the conceptual design.

During the conceptual design stage, Design Reviews usually consist of informal meetings held between the designer, his immediate supervisor, the section chief, and possibly with participation at higher levels of the organization when the importance of the design warrants.

At the start of a difficult or major development program, it may be desirable to extend the scope of and participation in these meetings by conducting formal, fully documented meetings utilizing the services of other well qualified members of the organization or outside consultants in certain specialties. Such meetings are generally called Formal Design Reviews.

Informal meetings generally are brainstorming sessions for the purpose of generating new ideas and to help the designer to develop an awareness of various problems, as well as to solidify design ideas. From these reviews, the designer develops sufficient confidence to proceed further into the Preliminary design phase.

1.2 PRELIMINARY DESIGN

Once the conceptual design review has been completed, the next step is the preliminary design. A layout is now required to determine how to install or assemble equipment into its particular area. To accomplish this, the designer lays out the particular area as near to full scale as possible. To assist the designer in visualizing how various designs will appear in a third dimension and also as an effective coordination tool with other system designers working on different functions, a mock-up should be utilized. The chief designer of an aircraft company referred to this as "a three dimensional layout for the designer." The mock-up at this particular stage should be very flexible in order that the designer can quickly get different ideas mocked up and be able to investigate many possibilities in a design for a given period of time.

The informal reviews continue on through the preliminary design phase to assist the designer in meeting milestones, staying within the budget, and arriving at a balanced design. When the preliminary design is complete, a Formal Design Review is held.

1.3 FORMAL DESIGN REVIEW

A great deal of organization and technical effort is necessary to provide the basic framework necessary for successful design reviews. Several principles have proven to be important regardless of specific program details:

a. The efficiency of design reviews is a direct function of the effectiveness of the communication techniques used between project, personnel, designers, reliability, competent specialists, etc.

b. Design reviews must be conducted in accordance with program milestone schedules and specific ground rules. A checklist or its equivalent must be used to assure adequate consideration of elements such as reliability vs. reliability requirements, and maintainability vs. maintainability requirements.

c. Design reviews must be to the point, brief, must not drift away from the topic under consideration, must be confined to essential personnel, must not include "interested" personnel.

d. Design reviews must make provision for corrective actions to be identified and monitored.

e. Design reviews must be adequately funded and data must be recorded to assure that the results can be evaluated at some future date.

Every project, every design for that matter, is evaluated with regard to its ultimate function, reliability, and maintainability. Whenever one circuit is selected over another or a part or a packaging configuration is chosen, the engineer has weighed some trade-offs and has made a decision as to the adequacy of one design versus another.

When actions such as these are performed on the basis of minimum information or is the result of empirical techniques which have evolved through the years there is a strong possibility for the creation of inadequate designs, costly errors and incompatibility as various segments of an equipment are integrated. Through design reviews we are able to assure ourselves of a uniform high quality of designs, even though hundreds of personnel are involved. The standards remain in the hands of a very few people. Even though most design reviews do not have the authority to reject a design, their influence is felt very strongly in the adherence to these standards.

Mutual exchange of technical information is of great advantage to program efficiency in product design. This cross-fertilization of design techniques through the medium of a design review improve the capability of all engineering personnel participating. The properly organized design review program utilizes the available capacity of specialists in an optimum fashion.

Contractually there are many difficulties most of which must be overcome in order to perform in accordance with contractual requirements. Design reviews are almost a necessity in dealing with subcontractors or associate contractors, particularly for the prime or the lead contractor. The monitoring of design reviews is difficult and yet in order to have an integrated weapon system it must be done. Few companies are willing to send copies of their design reviews outside their organizations. This is tantamount to telling the competitor what kind of problems they have. It is a private problem and this difficulty must be overcome when participating as a subcontractor or a co-contractor.

The primes must review the subcontractor and frequently must conduct a design review of the subcontractor's product themselves. For maximum system worth the design and the reliability efforts of all organizations must be compatible. The activities of companies with widely varying policies and design approaches must be integrated. In this type of effort the responsibility of the prime contractor is to coordinate, standardize designs, finishes, parts, components, reporting methods and frequently control the level of the engineers used on the job.

A subject which will come under frequent discussion is Bureau personnel attendance at contractor design reviews. The arguments presented in the preceding paragraph apply to this case too. Bureau engineers must realize that their attendance will tend to limit the free exchange of information and the open expression of divergent opinions on the part of contractor personnel. This will very likely result in the design review program being completely ineffective. However, cases may arise in which the Bureau has had a direct contact with the design process and is hence in a position to contribute significantly to the design review process. In such cases Bureau participation can be justified and is warranted. A good ground rule to be followed could be: attendance as an "interested party" or "observer" should be discouraged, attendance as an active participant should be encouraged.

But if, as one service has done, the Bureau wants to renegotiate contract dollars because of design effort scrapped as result of Design Review, further reviews with Bureau participation will be sheer white-wash.

The primary difference in the informal meetings and the Formal Design Review is that the Formal Review formulates more definite decisions. Also, aspects outside of Engineering are reviewed by specialists in Manufacturing, Tooling, Planning, Logistics, Purchasing, Facilities, and Quality Assurance. This provides the Designer with assurance that his design is progressing along practical lines. It is to provide assurance that the design can be (a) manufactured economically, (b) the equipment which has to be obtained outside of the company can be purchased, (c) the design can be serviced, (d) can be tested in production and at Receiving, and (e) can be provided with a Quality Assurance Program. During this review the information will be documented and maintained as a permanent record. The various specialists mentioned above form a Design Review Board. This Board is on call by its chairman.

If an effective job is to be done, it makes little difference where in the organization the design review board members report. The essential requirements are that the board, as such, must:

a. Report to a manager other than those whose designs are reviewed. No one can effectively audit his own work. Thus it may be established within the design assurance (related to engineering) area or the product assurance (reliability, quality, etc.) organization under general management. Or, it may be located within a design assurance (reliability, etc.) organization in Engineering, if separated from design responsibility.

b. Report high enough to attract and satisfy truly experienced engineers as review chairmen and participants.

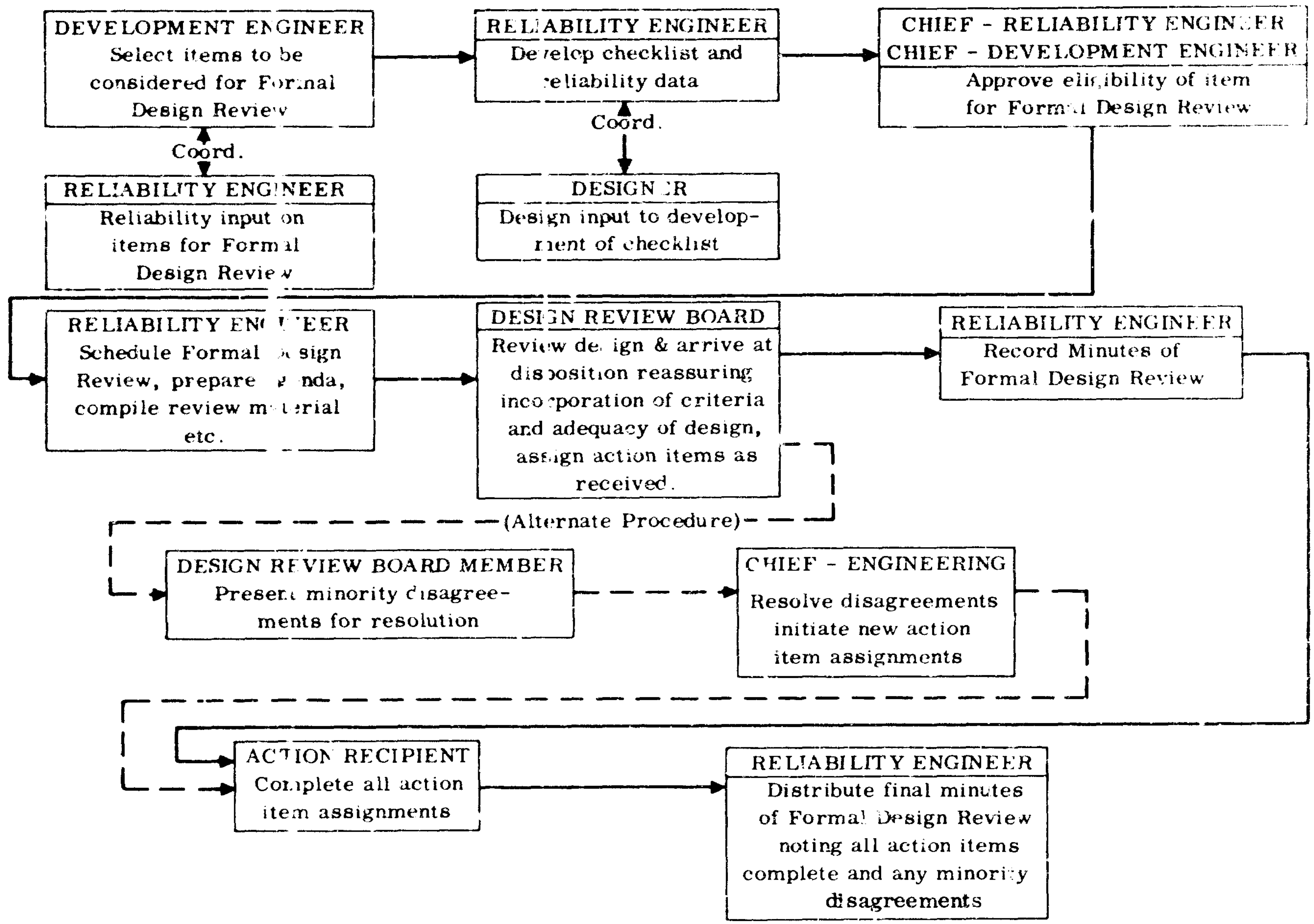
c. Have top-calibre men. Review chairmen must be technically experienced, diplomatic, able to recognize "snow", tough when the occasion needs it, and widely respected. Men of this calibre are available in most companies, but they command excellent salaries.

A general FLOW-DIAGRAM is shown in Figure 15-8 for a Design Review System. When the Formal Reviews are complete, the designer can now accomplish several steps toward completing his design and providing for the manufacturing of the design. Some of these steps are (a) write advanced material orders for both material and parts; (b) release information for a mock-up; (c) write some of the test plans and procedures; (d) order new facilities that may be required for manufacturing and tests; (e) provide information to Program Evaluation and Review Technique (PERT); (f) inform other designers who are depending on the progress of the design with up-dated information.

1.4 FINAL DESIGN

With Preliminary Reviews now completed, the designer can proceed to the final design phase which will develop the details required to make the components subsystems or system.

DESIGN REVIEW FLOW CHART



Preparation for a design review starts with the assembly of a data package on the design approximately two weeks prior to the Final Design Review of the design. This enables members of the board to become familiar with the design prior to the meeting and to formulate comments on the design to present at the Design Review. The major input to the data package must come from the designer. Two important benefits accrue at this point. (a) the designer must make a rather thorough review of his design in the process of preparing this material and (b) board members who have made prior input to the designer during the design process will check the validity of interpretation by the designer and the correctness of the information transmitted.

The Design Review Board should be headed by an experienced chairman. He calls the meeting, and conducts it. He asks the design engineer to describe the reasoning behind his design, and particularly behind unusual features and potential trouble areas.

He then asks for team attention sequentially to each agenda item. He runs through previously-selected items of the pertinent checklists, inviting comment. When design "soft-spots" are detected, he leads the discussion to bring out all viewpoints. He then expresses the team concensus of opinion, adjusts it until acceptable all around, and records it. Dissent, if any (it is rare if the team is competent), is recorded.

When a change is recommended, the design engineer is asked what action he will take. In most instances, he can respond on the spot. But if necessary, the engineer may take up to ten days to get more information, and is required then to respond.

The formal meeting is then closed, and a report issued. The report specified -

1. Areas of outstanding design.
2. What changes are recommended.
3. Why each change is recommended.
4. Who is asked to make each change.
5. When each change should be completed.

One of the most effective techniques for following up action on recommended changes is a Corrective Action Log. This names the department and individual responsible, the design identification, the action to be taken, the status of the action, the scheduled completion date, and the estimated completion date. An audit group controls this log, reissues it weekly, and makes sure that names stay on the list until action is completed by all concerned.

When action drags, a marked copy is sent to the supervisor of the man who should act.

When the final layout has been completed, a Formal Design Review is conducted in the same manner as described for the preliminary design but the review is oriented more toward the design details rather than the system conception. An agenda is again used. A much more specific review can now be made. This review assists the designer with information with which to evaluate and direct the detailed implementation of the design. That is, the review can consider parts applications, tolerance analysis, Reliability and Maintainability prediction vs. requirements, emphasis of certain dimensions, the need of production tests, the type of material processing, the assembly sequence, the areas of Quality Engineering emphasis and the schedule required on various parts for tests. Also, certain deviations from the customer's specifications may be required. In order to avoid delay when equipment is completed, deviation requests must be submitted early for customer approval.

The designer then proceeds to direct the completion of the design. Variations determined in the drawing of the details need to be noted on the layout as well as the part number of the detail. Also, a notation of the analytical record and reports is noted on the layout. Experiences have shown the well documented layout is invaluable when failures occur and corrective action is sought. The layout provides a central source of information and this enables the designer to quickly evaluate the background and saves much time arriving at a solution to a failure.

Final Design Review is now in order to evaluate the design, with the assistance of all of the knowledge possible prior to its final use. A checklist gives an idea of the considerations which must be made at this time. The various specialists on the Design Review Board assist the designer materially in providing information which finally can be best evaluated by the designer who knows the very "heart-beat" of the design. With this detailed information supplied by the Design Board, he can now make the final evaluation of the end item. This is the last opportunity for the designer to assure that his design will be successful as originally released.

1.5 ALTERATION OR CORRECTIONS

When design changes are needed after initial release, design review is of equal, if not more, significance than at previous times. The plan alterations, revisions and fixes are the indication of hidden problems. Because of their nature they require the most rigorous attention in design review for permanency of adequate solution. They are also the most costly in time and dollars, since they represent "re-do" of both design and finished manufacture, as well as requiring field changes and logistic cost if delivered.

In this area, the pressures on the designer to hurry the fix, obviate the onus of mistakes, release new material, recover from schedule delinquencies, etc., creates an environment that leans more to "get it fixed and out at any cost" than to considerations of the reliability; i.e., permanent adequacy of the fix. These pressures lead to relaxation of taking technical advantage of the lessons learned. Formal Review of the design must be required for any design change.

2. CHECKLISTS

Two types of checklists are used in conducting design reviews: (a) a design review checklist for use in preparation of the data package, agenda, and reports, and (b) technical lists for particular types of analyses. The completed agenda serves as a checklist for the design review meeting and the report.

The following paragraphs give examples of each.

2.1 DATA PACKAGE CHECKLIST

1. List all required functions of the component, system or problem, including allowable performance ranges, variabilities, and parametric variations.

2. List all environmental conditions by magnitude and frequency, including transients which the component must withstand in testing and during service life.

3. List all materials to be used in the system, component or part, with the properties of each under the environmental conditions expected. List the variability of these properties.

4. Outline complete test plan including requirements for any special test equipment.

2.2 GENERAL DESIGN CHECKLIST

1. Review all basic parameters included in the data package for correctness and completeness.

2. Examine the subject design or component to determine if provisions for each functional requirement have been included in the design. Establish the feasibility of holding these to specified variability in manufacture and define the level of confidence that must be generated to assure that the variability is within limits.

3. Note any capabilities, features, accuracies or specified tests which are beyond the state-of-the-art or beyond the functional capabilities of the design facilities.

4. Examine the design approach to determine if the simplest possible means for obtaining the required function has been developed. Reliability varies inversely with some power of the number of parts used.

5. Determine if proven (by test or similar application history) components and parts have been used wherever feasible.

6. Check the stress analysis (including structural) of each component or part, and determine critical loading and possible failure modes. Look for points of stress concentration or intensifications, and other possible weak lines (including limiting parameters to continuity of performance). Look for load concentrations due to externally applied shock; and for noise contributions.

7. Compare the resistive strengths (and any established allowables) of each material, with the calculated load stresses expected. Indicate the ranges of variability.

8. Examine the possibility, and the effects of deflection under load, of each component, or part, on the performance required from it function. Estimate external shock effects and resonant vibrations on performance and life expectancy.

9. Determine the compatibility of the material and finishes with each other, in assembly, under the expected environments. If data is not available, estimate testing requirements.

10. Consider the possibility and effects of predictable wear on the maximum allowable tolerances, as related to the performance factors of the components.

11. Consider the possibility and the effects of adverse tolerance buildup on each part, including the effects of thermal expansion, vibration, and differential shock excursions.

12. Consider the producibility of each component or part under the manufacturing conditions in which it will be built.

13. Consider the related aspects of accessibility, repairability, maintainability (including lubrication) and operability under field conditions with the variabilities of skill and morale of personnel.

14. Consider the convenience, special tools and accuracy required for operational adjustments and control instrumentation, from a human factors standpoint.

15. Consider the effects of associated random casualty and permanent shock effects on the performance characteristics of the total system.

16. Consider the compatibility of the components and parts with each other and with supporting services in the system.

17. Consider the installation criteria (handling, alignment, etc.) for the system, component or part in the overall arrangement.

18. Review the overall evaluation, summarize and conclude, noting:

a. The possible design deficiencies, including contract or specification deficiencies or conflicts.

b. The probable and possible modes of failure and the effect of these or both the component and overall system.

c. The tests deemed necessary to establish data for final reliability assurance.

d. Any inspection procedures either routine or special, which would help uncover most likely manufacturing and assembly errors.

e. The test deemed necessary to fully evaluate performance vs. design, failure modes, and overload conditions.

f. For parallel components or other components that can fail without causing a detectable system malfunction, list the periodic inspection procedures that will monitor these potential failure points.

g. The criteria (including time) for periodic preventive maintenance and repair.

h. The important operational cautions which should be included in instruction books and maintenance manuals.

i. Review life expectancy data and associated parametric criteria for failure vs. time. List suggested service life periods to component overhaul and/or replacement.

j. Review all data developed and failure/time information on similar components. Estimate a mean time to first failure and/or the safety margins available to assure compliance with contract requirements.

k. The developed information on probable life expectancies assuming adequate maintenance and repair performance. Establish level of essentially and list all inputs for establishing confidence in predictions.

l. List agreed actions to be taken by functional ine departments in connection with deficiencies, errors, or inadequate methods/procedures. Establish commitments and follow-up.

m. Write a factual report.

2.3 STRUCTURAL FATIGUE CHECKLIST

1. Was major attention given to actual stresses, especially at stress concentrations, rather than to the nominal average stresses?

2. Did you visualize how load is transferred from one part or section to another in a structure and/or the distortions that occur during loading, to help locate the points of high stress?

3. Were gradual changes in section and symmetry of the design used according to such design criteria as shown in Section XX of the Design Manual?

4. Was careful attention given to location of joints and type of joints used? (Joints are one of the most frequent sources of fatigue weakness.)

5. Were symmetrical joints used wherever possible?

6. Were suitable means used to stiffen unsymmetrical joints so that secondary flexing is reduced to a minimum?

7. Did you design joints so that all parts will participate equally, and that there will not be an undesirable load transfer to an adjacent part?

8. Did you avoid open holes and loosely filled ones?

9. Was preference given in the design to butt joints, as detailed in the Design Manual, Section IV, Chapter 5?

10. Did you give preference to redundant-type structures where this type of structure is possible?

11. Was careful attention given to fabrication details to improve fatigue life?

12. Were the proper surface finishes chosen?

13. Was suitable protection against corrosion provided?

14. Was attention given to the geometry of a welded joint including such factors as smoothness, undercutting, cracks, excessive porosity, spatter, and symmetry?

15. Did you design for accessibility for inspection of important tension joints?

16. Was the addition of secondary brackets, fittings, handles, steps, bosses, grooves, and openings at locations of high stress avoided?

17. Is part material compatible with its function and loading?

18. Is the type of construction best suited for the loading conditions including sonic fatigue?

19. Are the unsupported panel sizes small enough to resist sonic fatigue?

20. Has maximum simplicity been achieved consistent with sonic fatigue?

21. Is the part/assembly sensitive to fatigue from ground handling and vibration to be encountered?

22. Are there any unnecessary joints and splices?

23. Are there any possibilities of chain reaction-type failures which can be prevented?

24. Do the fastener selections best satisfy all load requirements?

25. Are fastener bolt sizes and tolerances compatible with part functions?

26. Has the proper bolt torque been specified?

27. Have retaining or locking rings been eliminated where possible?

28. Have the heat treat steels been considered for hydrogen embrittlement?

29. Has Design Manual plating practice been adopted?

30. Has ample clearance been allowed for structural deflection of adjacent parts?

31. Has effect of structural deflection of one part on others attached to it been considered?

32. Have thermal stresses and differential thermal expansion been considered?

33. Have the following sources of stress concentration been eliminated?

   a. Sharp corner and fillet radii?

   b. Eccentric load paths?

   c. Abrupt section changes?

   d. Stiffeners terminating in middle of unsupported panels?

   e. Clip angles attached to web only?

   f. Steel stamp part numbering in areas of high stress?

34. Is secondary structure, which is rigidly attached to primary structure, designed to carry the loads induced in it by deflection of the primary structure?

35. Has the primary structure been reviewed for adverse load distribution caused by secondary structure?

2.4 HUMAN FACTORS CHECKLIST

1. Has the best allocation of function between man and machine been determined?

2. Have the controls and indicators been designed and arranged with body measurement limitations duly considered?

3. Has the location of indicators and controls been balanced against the need for adjustment?

4. Has consideration been given to the use the operator will make of each instrument, control, and equipment and as to how its location will aid in the performance of the task with the most accuracy and least fatigue?

5. Has the type of response he must make been determined?

6. Will present design interfere with his ability to continue receiving the information he needs?

7. Is speed of operation critical?

8. Is accuracy of reading or setting critical?

9. Have the job operations been simplified to present to the operator the fewest possible motions, the nature sequence of motions and only pertinent information, in order to minimize the chance of failure under stress?

10. May adjustments and alignment be accomplished by an average technician?

11. Has consideration been given to the operators psychological and environmental conditions during the operation of the equipment?

12. Have the different kinds of illumination been considered?

13. Have glare hazards been eliminated, such as brightly polished bezels, glossy enamel finishes, or highly reflective instrument covers?

14. Have the static dimensional data for cabinets, racks and consoles been used in the design with the dynamic dimensional statistics of the human operator in mind?

15. Are vertically mounted visual displays 50 to 70 inches above the floor when they are to be viewed for a standing position?

16. Has a 30-inch seat-to-eye height reference been used to locate visual displays for a seated operator and has the chair height been specified along with the console dimensions?

17. For a comfortable display mounting angle, has the following rule been used: 60 degrees from horizontal for seated operator position, 45 degrees for a combination position of sitting or standing and 30 degrees for a standing position?

18. Has a 28-inch arm reach, measured from the operator's shoulder, been used as a limiting figure for the placement of controls which are to be used often?

19. Have the controls been located near the display which they affect when this does not conflict with other manipulatory requirements?

20. Have the controls been arranged sequentially with respect to be expected or required order of operation?

21. Do arrangement and layouts stress the importance of balancing the workload or do they force one hand to perform too many tasks while the other hand is idle?

22. Considering functional requirements, is the panel layout as simple as practicable.

23. Are interdependent functions so arranged that adjustment and troubleshooting are amenable to logical, straight forward procedures?

24. Do visual displays occupy central areas and controls occupy peripheral areas whenever possible to avoid hand and arm interference with visual tasks?

2.5 DEVELOPMENT OF CHECKLISTS

It is apparent that the checklists should be prepared by the man or group most competent in the specialty. In the conduct of the meetings a complete agenda should be used to assure nothing is omitted. Points of no consequence can be summarily discussed and disposed of. The technical checklist should be prepared by an experienced specialist who contributes his knowledge of the pattern of error he has discerned in his experience with a wide variety of designs.

The technical checklists should be furnished to the designer in the very early stages of design. They should be devised for convenient use during the design phase and should be required to be submitted to his supervisor with the completed design, along with analyses and other documentation.

3. COVERAGE OF DESIGN REVIEW

It is obviously impractical and inefficient to conduct separate reviews of Reliability, Maintainability, Producibility, Testability and the dozens of other disciplines. The design review should comprehend all of the factors that make a good design. In the paragraphs that follow, some of the aspects will be covered.

3.1 MAINTAINABILITY

One of the major areas of review is the maintainability of the product. The design must be subject to review by those who plan, design and have the responsibility for support of the weapon during its operational life. This is accomplished primarily by a maintenance engineering analysis of the end article, systems and components thereof by a group external to the design engineering department.

Successful implementa on of a competent maintenance engineering analysis (MEA) requires management support, proper funding, proper planning and most important, personnel with the proper background and training. The MEA changes recommended must be considered from all aspects including necessary tradeoffs of cost, weight, performance and mission accomplishment. Thus the MEA must be a part of the design review.

To be effective, the MEA should be initiated during the proposal stage and carried forward during drawing layout, drawing release, parts manufacture, and assembly and test of components and the end article.

The maintenance analyst must know the maintenance level at which each bit, piece, part, component, system or end article will be serviced, repaired or overhauled. The analyst must establish the detailed maintenance tasks required to maintain the end article in, or return it to a mission ready status. The analyst must justify the tools and test equipment required to accomplish each task. He must source code the parts required to accomplish each task and assign procurement factors as to quantities required. He must be able to identify any new special skills required to perform the tasks and determine that such skills will be available at the using activity. He must determine that the necessary technical instructions will be available to the man performing the task.

3.2 PARTS CONTROL

One of the major causes of unreliability is the use of unreliable parts. The designer has a penchant for using new and novel ideas based on apparently outstanding performance capabilities seen in reports or advertising without verification of the actual performance of the part. Since parts, just like systems must be developed, the bugs eliminated and the design matured to reliable operation, such innovations, more often than not, create reliability problems. Parts specialists study the actual data on parts utilization to determine the degree of maturity of many parts, and can provide records of actual successful applications of the parts in many systems. Such a record of satisfactory use provides some reasonable assurance of success in similar applications. Where no evidence of successful use can be found the use of the part is suspect. The parts specialist, in addition to being available for information on past uses, should review the parts proposed to identify such suspect applications.

3.3 MANUFACTURING PROCESS ENGINEERS

While the designer is the expert on the requirements of the final product, he is not necessarily expert in the manufacturing processes necessary or useful in achieving such requirements. The capability of the manufacturing tools and machines is the province of production engineers. These latter can discover areas in the design that cannot be built within the tolerances assigned using equipment available in the plant. They can propose changes in the specifications and drawing which, if acceptable, will permit accomplishment with available tools, better inspection or less expensive manufacture. Their day in court at a design review frequently improves the producibility of the product without degrading (and often improving) performance and reliability.

3.4 RELIABILITY ENGINEERS

The position of the Reliability Engineer is that of the critic. The designer is primarily oriented toward seeing that the design will work, whereas the critic, or Reliability Engineer, is attempting to ferret out those areas which would cause the design not to operate, the indication of its unreliability.

By systematic approaches of the mathematical model, failure effect analysis, and criticality lists, the designer can be materially assisted in arriving at the portions of his design that he must concentrate on in order to arrive at a balanced and reliable design. In a complex system, this always is a difficult assessment for the designer to make without the services of the service type of organizations. Since the mathematical model is a systematic functional diagramming of components as they fit into subsystems and systems, this model can materially aid the designer in having an overall feel for the complete system. This, in turn will help him in providing designs that will provide reliability for the total system rather than overdesign a particular portion of it and thereby not improve the total reliability.

3.5 QUALITY CONTROL ENGINEERS

The assurance that the manufactured article conforms to the specifications is the province of Quality Control. Their participation in design reviews will assist the designer in making sure that the required quality is specified and that the necessary controls and inspections can be performed to assure that it is achieved.

4. EFFECTIVENESS

Fear of things not understood is often a constraint upon design review. Such fear turns gradually into appreciation once an engineer realizes how much he has been helped; how he has been protected from the consequence of mistakes. The poor engineer may risk exposure of his inadequacies, but the good engineer reaps the benefit of expert appreciation of his capabilities.

Perhaps the greatest single benefit of design review is the discipline of preparation for it. Analyses and tests are made that otherwise might be omitted, checklists are checked and rechecked, and there is more prior communication with the specialists. And this is the path of good design.

Design Review is a service and audit for which manpower must be budgeted. But the longer-term savings can far offset this cost. To the extent that design review helps get work done right the first time, it can minimize or eliminate overrun, improve profit, and improve competitive position. Specifically:

1. Training: The discipline of organized preparation for design review, and participation therein, amounts to quicker on-the-job training of young engineers. Thus their learning curve is steeper, with better efficiency and fewer costly changes.

2. Specialists: Fuller utilization of specialist skills brings earlier design adjustments, avoiding the cost of later changes.

3. Requirements Review: Critical examination of customer stated and unstated needs and constraints can (a) uncover unrealized requirements that otherwise cause schedule slippage and unbudgeted cost, (b) avoid wasted design effort and cost on non-essentials, and (c) avoid the boomerang cost of personal "understandings" between company and customer personnel.

4. Preferred Components: Many parts and assemblies are useful across many projects. The selection and establishment of preferred components, for required design use where feasible (a) reduces procurement cost through higher volume, (b) reduces factory, field, and customer inventory cost, and (c) improves reliability through better but less costly test and field information feedback, and higher reliability reduces factory, field and customer costs. Design review assures the use of preferred components where feasible.

5. Value/Cost: The techniques of "value analysis" have long been used for substantial cost reduction after release. The same techniques can be used at all levels of the design hierarchy to better approach minimum cost for the required values before the design is laced and rigid so that the opportunity is lost. Also, the cost-effectiveness techniques for system evaluation, based upon "reliability" models, provide a powerful tool for visibility of consolidated effects of proposed changes. Effective design review requires these analyses.

6. Changes: To the extent that the above techniques detect the need and path for correction at the earliest possible time during design, they can substantially reduce the cost of design, design changes, redesign, confusion, test, rework, scrap, maintenance, and failure consequence.

5. REFERENCES

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Chapter 16

FAILURE DIAGNOSIS

Chapter 16

FAILURE DIAGNOSIS

In spite of the care with which the design is performed and the production processes controlled, only an incurable optimist will expect a perfect product. As realists, we must admit that malfunction will occur. To provide for elimination of defects during the production and operational phase, every effort must be made to identify weaknesses in the product as soon as they manifest themselves. One of the program elements leading to identification of weaknesses in the product, and eventual correction, is the failure reporting and analysis effort.

1. CAUSES OF FAILURES

1.1 BASIC CLASSIFICATIONS

A malfunction of equipment may occur due to any one or a combination of three basic causes:

(a) Weakness in the design;

(b) Error in manufacture, assembly, inspection or testing;

(c) Error by the operator or maintenance mechanic.

1.2 EXCEPTIONS

In addition to these three basic classes, two other types of malfunction are reported. Secondary failures are malfunctions caused directly or indirectly by the malfunction of an associated part or component. The failure should be charged as a primary failure to the part or component whose intial malfunction caused the secondary failure. In some cases a reported failure cannot be confirmed. In many such cases the report of the failure was a kind of operator error. Many things can cause an operator to report a failure and replace an unfailed item -- misreading a dial, covering up some mistake of his own, being misled by noise or vibration initiated somewhere else. It is important to remember that not all reported failures are identifiable or correctible.

2. IDENTIFICATION OF CAUSES

The foundation of a failure diagnosis and corrective action program is an effective failure reporting system. (Figure 16-3). Every failure, regardless of cause, should be reported. One

BUSHIPS ELECTRONIC EQUIPMENT FAILURE REPORT

ELECTRONIC EQUIPMENT FAILURE/REPLACEMENT REPORT DD-787 (PROPOSED) — REPORT BUSHIPS 10550-1

1. DESIGNATION OF SHIP OR STATION

2. REPAIRED OR REPORTED BY

NAME	RATE	AFFILIATION
		1. ☐ U.S. NAVY 2. ☐ CONTRACTOR 3. ☐ CIVIL SERVICE

3. TYPE OF REPORT (CHECK ONE)
1. ☐ OPERATIONAL FAILURE
2. ☐ PREVENTIVE MAINTENANCE (POMSEE)
3. ☐ PREVENTIVE MAINTENANCE (NOT POMSEE)
4. ☐ STOCK DEFECTIVE
5. ☐ REPAIR OF REPLACEABLE UNIT OR PLUG-IN ASSEMBLY
6. ☐ OTHER

4. TIME FAIL. OCCURRED OR MAINT. BEGAN

MONTH	DAY	YEAR	TIME

5. TIME FAIL. CLEARED OR MAINT. COMPL.

MONTH	DAY	YEAR	TIME

EQUIPMENT

6. MODEL TYPE DESIGNATION

7. EQUIP. SERIAL NO.

8. CONTRACTOR (NAVY CODE OR COMPLETE NAME)

9. FIRST INDICATION OF TROUBLE (CHECK ONE)
1. ☐ INOPERATIVE
2. ☐ OUT OF TOLERANCE, LOW
3. ☐ OUT OF TOLERANCE, HIGH
4. ☐ INTERMITTENT OPERATION
5. ☐ UNSTABLE OPERATION
6. ☐ NOISE OR VIBRATION
7. ☐ OVERHEATING
8. ☐ VISUAL DEFECT
9. ☐ OTHER, EXPLAIN

10. OPERATIONAL CONDITION (CHECK ONE)
1. ☐ OUT OF SERVICE
2. ☐ OPERATING AT REDUCED CAPABILITY
3. ☐ UNAFFECTED

11. TIME METER READING
- A. HIGH VOLTAGE
- B. FILAMENT /ELAPSED

12. REPAIR TIME

MAN-HOURS	TENTHS

REPLACEMENT DATA

13. LOWEST DESIGNATED UNIT (U) OR SUB-ASSEMBLY (SA)	14. LOWEST DES. U/SA SERIAL NO.	15. REFERENCE DESIGNATION (V-1, C-14, R11, ETC.)	16. FEDERAL STOCK NUMBER	17. MFR. OF REMOVED ITEM	18. TYPE OF FAILURE	19. PRIMARY OR SECONDARY FAIL ?	20. CAUSE OF FAILURE	21. DISPOSITION OF REMOVED ITEM	22. REPL. AVAILABLE LOCALLY ?
						P ☐ S ☐			Y ☐ N ☐
						P ☐ S ☐			Y ☐ N ☐
						P ☐ S ☐			Y ☐ N ☐
						P ☐ S ☐			Y ☐ N ☐
						P ☐ S ☐			Y ☐ N ☐

23. REPAIR TIME FACTORS

CODE	DAYS	HOURS	TENTHS	CODE	DAYS	HOURS	TENTHS

24. REMARKS (CONTINUE ON REVERSE SIDE IF NECESSARY)

procedure, found effective in industry, is to use the failure report form as a requisition for new parts so that the drawing of a part from stores automatically reports the expenditure. When this system is used, obviously, some additional procedure is necessary to obtain reports of failures repaired without procurement of a new part. A report should be prepared at the time of failure and should include at least the following:

(a) Identification of the failed part. (Part name, part number, serial number, identification of next level of assembly).

(b) Identification of replacement part.

(c) Operating life data on the failed part.

(d) Date and activity area when failure was discovered (Manufacturing, test and operation).

(e) Failure symptoms. (Narrative or coded mode listing or both).

(f) Cause of failure. (narrative or coded mechanism listing or both).

(g) Action taken to restore system to operation (i.e., replaced part).

Data collection systems are covered in detail in Chapter 9.

2.1 FREQUENCY OF OCCURRENCE

One of the indicators in identification of a problem area is the excessive occurrence of failures. A large number of reported failures on any particular part number should be investigated to determine if a problem exists. The first step is to identify the assembly in which the failures are occurring. If a large number of that part number are installed in different locations and if the failures are occurring at different locations more or less at random, the part itself is suspect. If the failures are occurring at one or a few of the locations, the examination should be made of the system or assemblies in which the parts are failing.

Even a few failures of a particular part in a particular assembly should initiate an investigation.

2.2 CIRCUIT ANALYSIS

A reliability problem can be identified from an excessive number of failures. Even a single failure can indicate a reliability problem, however, when the circuit application is such that the failure will prevent accomplishment of a required function, or when safety of operating personnel may be involved.

When a problem area is identified, the application of the part or parts should be re-evaluated. The circuit analysis or component stress computation should be reviewed to re-establish the designed stress levels (voltages, pressures, etc.) and the imposed environment. The mechanism of failure, identified in the failure report, should be evaluated against design parameters. Where the failure appears improbable in light of the stress margins used in the design, an extension of the analysis to associated subsystems, possibly even measurement of the parameters in the operating environment may be indicated. Where the cause of failure cannot be identified from circuit or design analysis, a failure analysis should be performed.

2.3 FAILURE ANALYSIS

Failure analysis is the determination of the cause of failure of equipment from test and inspection processes. Those component malfunctions that are identified as problem areas, but not diagnosed from re-evaluation of the design are taken to a testing laboratory. In the laboratory, unless the nature of the failure is apparent from inspection, the equipment is set up on test in an assembly simulating its actual operational use. In the test assembly it is operated to ascertain the nature of the malfunction, and to verify that it is not operating as designed. Readings are taken of significant parameters to define exactly how the equipment operates.

Having verified the failure (or that no apparent malfunction is occurring in the test set-up) the equipment is disassembled, inspected and measurements of important dimensions compared to the drawings. Where indicated, chemical or metallurgical tests or examinations are conducted. As a result of tests and examinations, the analyst prepares a report covering:

(a) Previous history of failures of the part number including causes of failure ascribed.

(b) Significance factors in the original report of failure of this part, including actual and possible effects of the failure.

(c) Mode of this failure, or report that failure cannot be caused to recur.

(d) Cause of the failure, i.e., improper clearance, corrosion, faulty soldering.

(e) Whether failure is classified as "design defect" or "not in accordance with design specifications."

(f) Recommended corrective action.

Failure analysis should be continued until the cause and means of correction are identified. This may require special instructions to ship every failed part to the laboratory, or trips by analysts to the sites of failure, or assembly of "Tiger Teams" of designers, technicians and laboratory people. Where the consequences of failure are serious, special restrictions should be placed on the use of the part until the problem is solved. Once a fix is decided, the part should be kept under surveillance to assure that the "fix" corrects the problem. Experience has shown that all too often a first fix only corrected an obvious manufacturing defect leaving an underlying system design defect still uncorrected.

2.4 EXAMPLE OF FAILURE ANALYSIS REPORT

2.4.1 Component Identification

(a)	FAR Number Failure Report No.	CT-59-24-146 925944
(b)	Part Name	ACCELEROMETER
(c)	Manufacturer	(xx..........x)
(d)	Part Number	KA-1006
(e)	Serial	C078B
(f)	Next Assembly	55-11010

2.4.2 History

(a) The accelerometer reportedly failed on April 19, 1963 at the Astronautics Standards Laboratory during or before calibration when the lead wire to the accelerometer pickup was found to be broken at the pin connector junction.

(b) The accelerometer senses vibration in the booster jettison track support area. It is one of five accelerometers used on Centaur upper-stage booster.

(c) The accelerometer consists of a piezoelectric sensing head, and a transistorized amplifier. The sensing head is connected to the amplifier by four feet of cable. The range of the accelerometer is $\pm$ 30 gravities.

(d) Nineteen of these accelerometers reportedly failed, according to Astronautics trend reports, for various reasons, in the six months preceding April 19, 1963. Four reportedly failed in the last 30 days of this period. Four accelerometers were failure analyzed, but none failed in this mode.

(e) Failure of the accelerometer with a broken lead wire would make the unit inoperative. Failure of this mode during flight would not affect vehicle operation, but would prevent the monitoring of vibration conditions during the mission.

2.4.3 Analysis

(a) Visual examination of the accelerometer pickup-confirmed the reported failure: the lead wire to the sensing head pickup was severed at the pin connector junction. A section through the pin connector's plastic jacket revealed the characteristics of the pin connector junction for a view of the lead wire, pin connector, plastic jacket, and the sensing head.

(b) Microscopic examination of the pin connector showed the center conductor of the coaxial cable lead was still soldered to the center terminal of the connector. The braid from the coaxial cable shield was also still soldered to the crimping ring of the pin connector clamping around the cable.

(c) Close examination of the broken lead wire revealed all the shield wires were twisted and bunched on one side of the center conductor insulation, and they were broken off at irregular lengths. This would indicate the lead wire had been subjected to a twisting motion, resulting in weakening of the shielding cable.

(d) The pin connector and coaxial cable adaptor fitting were externally coated with a red sealing compound, tending to restrict the free movement of the pin connector cap on the housing. This condition permitted the housing and the attached coaxial cable adapter to rotate while the pin connector was being secured to the sensing head by the pin connector cap. The only way to prevent the twisting of the coaxial cable, and its cable adaptor on the pin connector during the connection of the pin connector to the sensing head, is to grasp the plastic jacket surrounding the pin connector fitting. Since this adaptor fitting has just a 3/16-inch diameter, and 1/2-inch length, it must be grasped carefully if a twisting movement is to be prevented during connection.

(e) The pin connector fitting on the coaxial lead cable does not have an adequate design strength at the cable adaptor fitting to withstand twisting or bending movement of the cable, during the connecting process. Therefore, the shielding surrounding the center conductor will break when it is subjected to these extraneous or excessive movements during connecting or handling.

2.4.4 Conclusions

(a) The accelerometer failure: broken lead wire, was confirmed by visual examination. Microscopic examination of the lead wire and the pin connector revealed the coaxial cable lead had been subjected to a twisting motion that had weakened, and then broke, the shield cable. The small center conductor also broke, due to fatigue failure, as a result of the twisting movement to the cable.

(b) Failure was caused by a twisting action introduced into the coaxial cable lead during connection of the pin connector to the sensing head.

2.4.5 Recommended Corrective Action

(a) The Reliability Failure Analysis Group recommends the following corrective action to prevent breakage damage to the accelerometer coaxial lead cable during its connection into the sensing head, and during handling before installation:

(a) Use extreme care, when using the coaxial lead, not to twist or stretch the shielding directly below the rubber insulation.

(b) Grasp the plastic jacket surrounding the pin connector fitting firmly, when screwing the pin connector into the sensing head.

(b) The Reliability Failure Analysis Group recommends the following vendor design corrective action to prevent breakage damage to the accelerometer's coaxial lead cable, during handling and installation on Astronautics missiles:

(a) Improve design of the pin connector adaptor so the coaxial cable is given adequate support and is restrained from excessive twisting and bending.

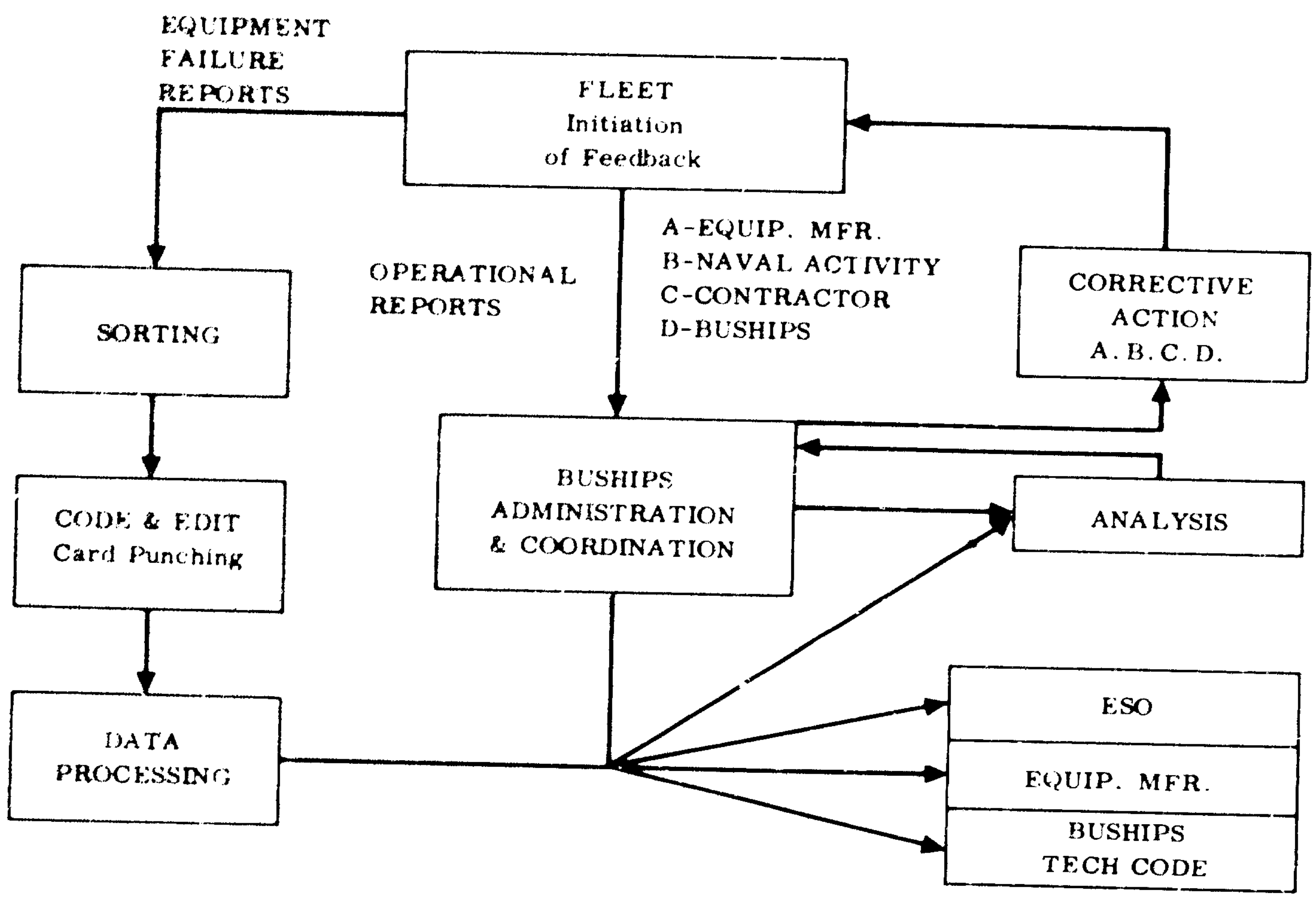
(b) Eliminate use of the red sealing compound on the shank of the pin connector, thereby reducing the twisting motion of the pin connector produced by the interference with the compound while the connector cap is threaded onto the sensing head.

2.5 CORRECTIVE ACTION

Once the cause of and responsibility for the malfunction has been determined, positive steps must be taken to assure that the information is used to eliminate the problem and prevent re-currence of the malfunctions (Figure 16-10). Responsibility should be assigned to an individual in whatever group the action to be taken might lie. One useful technique is the maintenance of a corrective action log as suggested in Chapter 15. The Corrective Action Log is a management report listing all known reliability (and other) problems with recommended solutions and names of persons responsible for carrying out the action. The log is updated and published weekly (daily in some critical operations). No entry is removed until an appropriate action taken by the person responsible is accepted by the program manager.

When a reliability problem of significance is identified due to a malfunction or part failure, the problem should be logged and assigned either to the design group responsible, or to the failure analysis group. The latter assignment is usually pre-ferred, since malfunctions are commonly caused by defects in manufacturing and/or operator error. The analyst should consult with the designer and manufacturing personnel as necessary to establish the facts. At this time, the responsibility is trans-ferred to an "action" man in design or manufacturing, with recommendations as to possible solutions. The "action" man is not bound to accept the recommendation of the analyst. His responsibility is to provide an acceptable solution.

FAILURE REPORTING



3. TIMING OF CORRECTIVE ACTION

Up to the present time, much of the emphasis associated with failure reporting and corrective action has been placed on programs associated with production efforts and, to a somewhat less extent, programs associated with field use by the customer. This is undoubtedly brought about by the fact that the need for corrective action is most obvious, perhaps even an absolute necessity, during this period. This is also the period during which the most data is available on which to base corrective action.

3.1 ENGINEERING TESTING

This normally is the first phase in the evolution of a system which produces satisfactory test data. The system design has progressed from the drawing stage to the model stage and the design itself should be fairly firm. Test data should be reasonably representative of the final system. This data comes from testing at all levels of equipment complexity, and is available from a number of types of testing such as environmental testing, reliability life testing, performance testing, and acceptance testing.

The analysis of failed subassemblies or systems is carried to the point of determining the basic component/part, connection, or structural failure. This analysis is documented by a Failure Analysis Report. This report documents the failure data at the component/part level and the corrective action required.

3.2 PRODUCTION

Due to the nature of the production phase of a program, there is an urgent need to obtain failure data and take any required corrective action as rapidly as possible.

If component/part failures are involved, an analysis of these parts is normally required in order to determine whether the failure is a result of design or application, assembly, quality control of parts as received, or an unsatisfactory type of component. The request for this component failure analysis plus the failure data and the initiation of corrective action can all be documented by using the Failure Analysis Report. All of the approaches mentioned above for failure reporting and corrective action with regard to production have dealt primarily with single failures or a specific problem area. To determine any significant trend in failures which may require additional corrective action, a summary report of failures is needed in order to determine broad corrective action requirements and achievements.

3.3 OPERATION BY CUSTOMER

This is the final phase of system evolution and is the one toward which all reliability efforts and corrective actions are directed. It is the system performance and reliability during this phase which determines the value of all prior reliability efforts and corrective action programs. Further correction action beyond that taken in the previously three phases can still be taken and is often necessary but, as mentioned earlier, is accompanied by a number of severe penalties.

4. SUMMARY

An important by-product of testing should be the discovery of residual causes of unreliability and the resulting corrective action to reduce or eliminate these causes. Experience has shown that the key to corrective action is competent analysis of each failure.

4.1 PREVIOUS LACK OF INTEREST

The need for failure analysis has been hampered by the fact that, traditionally, test specifications have assumed that the buyer's interest was limited to obtaining failure free devices that would pass all specified tests with a failure rate of zero. It has usually been stated or implied that if failures occurred, the devices ceased being of interest to the buyer and responsibility for analysis and removal of the cause of failure was the private concern of the contractor. The interest of the buyer would be resumed after an improved device had been submitted and had passed all tests.

4.2 RECOMMENDED REQUIREMENTS

This traditional treatment of failures occurring during test is unacceptable for military equipment. The probability is high that some failures will occur during earlier testing programs. The buyer is vitally interested in the diagnosis of test-produced failures and the procedure to be followed must be an inherent part of the procurement specification. The following items are proposed as mandatory specification requirements.

(1) Competent engineering failure diagnosis is mandatory for all failures.

(2) To the extent possible, each failure must be assigned a cause such as test instrumentation defect, test operator error, part failure, part deterioration, circuit tolerance failure due to designer's failure to allow for normal part variations, etc.

(3) Where failure occurs in an equipment under test, the pertinent damaging stresses must be carefully measured and recorded. As an example, if a capacitor fails, the possible damaging circuit stress (voltage, or sometimes current) must be measured and recorded. Furthermore, the possible damaging external stresses (temperature, humidity, etc.) must also be measured and recorded.

(4) Where practicable, disassembly and analysis must be performed on failed or deteriorated parts. A competent diagnosis must be made in terms of specific design features and specific workmanship, production engineering and inspection procedures. Where applicable, the failure diagnosis shall include an analysis of contributing causes such as inadequate circuit design (which will not, for example, tolerate normal part variations plus expected part deteriorations).

(5) A fully descriptive report or report section must be written for each failure. The report must assign the cause and responsibility and cover the diagnosis as outlined above. Where appropriate, recommendations for corrective action should also be included.

4.3 CONTRACTORS DESIGN EXPERIENCE

It should be mentioned that often the designer's knowledge is virtually indispensable to adequate diagnosis. Thus the contractor should be encouraged to maintain a nucleus of his applicable design group intact for the duration of the reliability tests, and to insure that this group is available for failure diagnosis activity after start of operational use. It is important that the failure diagnosis personnel be reasonably free from undue pressure by the buyer and/or other groups in the contractor's organization that may tend to restrict the investigations and produce inadequate diagnosis or even concealment of true problems. Since most of this pressure results from efforts to meet schedule and price commitments by the contractor, it may be that some relief must be extended by the buyer in this regard in order to gain the desired results.

5. REFERENCES

(1) Proceedings of the Seventh National Symposium on Reliability and Quality Control, January 9-11, 1961.

(2) AGREE Report by the Advisory Group on Reliability of Electronic Equipment, Office of the Assistant Secretary of Defense (Research and Engineering), 4 June 1957.

(3) Reliability Requirements for Shipboard and Ground Electronic Equipment, MIL-R-22732.

Chapter 17

SPECIFICATIONS

Chapter 17

SPECIFICATIONS

In contracting for systems and equipment, the "specification" is a primary tool used to describe exactly what is required and the ground rules under which it is to be developed. The Bureau is interested in obtaining a product which will perform specified functions under well-defined conditions, can be operated and maintained, will withstand the rigors of handling, use and environment, and can be repaired on occasion. To obtain this result, the specification must describe in precise detail what is wanted, and frequently how the contractor must perform some of the work.

No specification can be really complete in itself. Section 2 of standard specification format providés a listing of referenced documents, frequently with the statement.

> "The following specifications, standards, drawings and publications, of the issue in effect on date of invitations for bids, form a part of this specification."

Although this statement contractually invokes the additional requirements fully, administration of such a requirement is not automatic or invariant unless specific applicability details are included in a requirement paragraph in the basic individual system or equipment specification. This is so because (a) contractors past experience is that many of the clauses apparently invoked by reference have neither been required nor desired by the customer, and (b) the conflicts between clauses in referenced documents often preclude a clear understanding by the contractor or inspector as to what is required.

The specification "tree" is a natural and logical system. It is difficult to conceive how the procurement of complex systems and equipment could be done without it. But the weaknesses must be recognized. The sheer bulk of references, and their references in turn ad infinitum, tends to obscure the meat. It is not uncommon for a few basic specifications to in turn pick up a total of 3000 specifications. The referenced specifications almost invariably contain restrictive clauses, alternates and limitations. They nearly always contain material not applicable to the procurement. Failure to define precisely what is wanted has led contractors to performance of work not desired by the customer, and conversely, to contractor failure to perform desired work.

1. R&M SPECIFICATION CONSIDERATIONS

Reliability and maintainability are characteristics that cannot be determined by inspection. They can never be determined absolutely in test programs. The samples tested represent only a small portion of the systems built to the design. So in practice, the customer must have some measure of visibility and control of the contractors effort toward reliability and maintainability quantitative requirements, as well as evaluation of his progressive achievement of these requirements.

This visibility and control is established through the specification imposed on the contractor, and it has become customary to include all those tasks, tests and reports the contractor must perform and submit for the customer to have visibility and control. At the same time, there is a growing feeling that there is much "over-control", and hope that more incentive contracting will permit simpler controls.

As mentioned above, there are few instances where a specification will be applicable, in its entirety, to a particular program. Most of the time one or more specification sections can be eliminated because they are not germane to the program, or because their requirements are too severe or unrealistic. Specifications are usually written to cover, in a general sense, the "worst case" application of the equipments whose characteristics they govern.

For example, the ambient temperature range may be quoted in a specification as being from -54°C to 65°C. Equipment design to this specification must perform equally well at the Equator as at the North Pole. General purpose Military equipment may be required to function at either of these locations and should be designed to accommodate this wide latitude in ambient temperature. Special purpose units which will function in a temperature controlled environment, may find the temperature extremes of such a specification to be far in excess of what they will ever experience. In such cases the cognizant engineer should reduce the requirements of the specification for the procurement in question, which will generally reduce acquisition cost and improve delivery.

Reliability and maintainability specifications follow a similar pattern. Test programs specified for electronic systems are normally based on the fact that they include large numbers of identical parts. This fact controls the program requirements in several ways: (a) demonstration of achievement using a sequential test plan is usually practical, (b) reliability to be expected from parts from a particular supplier is relatively predictable, and (c) assembly processes can usually be controlled by statistical sampling.

Where these conditions apply, the basic programs recommended by the AGREE report (1) provide a reasonable approach to the achievement of acceptable reliability. Where these conditions do not obtain, different approaches are usually required.

To obtain a system or equipment that meets Bureau and fleet reliability and maintainability needs, (a) quantitative requirements for reliability and maintainability must be specified and (b) means for assuring that the requirements have actually been achieved must be established by the specification.

1.1 R&M SPECIFICATION EXPERIENCE

The specification of reliability requirements have in the past followed one or more of the following patterns:

a) No mention of reliability or quality control in the specification.

b) General statements, such as "Equipment shall have maximum reliability", "The principle of reliability is paramount and no compromise shall be made with other basic requirements of design", or (MIL E 16400:3.1) "Reliability shall meet the needs of the Naval Service."

c) Requirement for inspection during manufacture.

d) Requirements for qualification prior to award.

e) General life requirement, with or without specifying operating time to first major overhaul.

f) Specification of numerical Reliability "goals", not contractual requirements.

g) Specification of reliability requirements with verification procedure.

h) Specifying that the contractor shall analyze the needs and establish reliability requirements and verification criteria.

i) Specifying that various program tasks (prediction, testing, design review, failure diagnosis) be performed.

1.2 KINDS OF SPECIFICATIONS

Specifications designed to achieve the required reliability and maintainability design and development of a system or equipment, or to assure that a procured equipment meets the requirements, can be separated into three groups:

a) Establishment of quantitative goals.

b) Contracting for quantitative requirements and verification.

c) Contracting for tasks to be performed by the contractor.

In the first group, the quantitative goal is subject to other requirements of the specification and contract. It has no contractual standing. Meeting the goal is a matter of "good faith" on the part of the contractor, subject to compromise with contractual requirements, to lack of knowledge, understanding or appreciation.

Contracting for quantitative reliability and maintainability, with verification by "demonstration" or testing, provides the Bureau with data to evaluate the equipment. In contractual terms it requires the contractor to perform certain tests and provide the data. The quantitative requirement is a performance attribute of the specific system or equipment being procured. It is appropriate to include it in the specification, along with the use conditions and exact function of the product. The type of test that can be performed is peculiar to the system or equipment, and should be defined to some degree in its specification. The extent of testing is dependent upon the requirements for a particular application and may vary from one procurement to the next.

In the third group, the contract requires the performance of specific tasks. The customer is buying efforts which are considered to achieve or at least improve reliability and maintainability, rather than any particular attribute of the system or equipment. However, the specification of analytical tasks is completely identifiable to the intended application of the specification, rather than a product attribute. As such it should not be included in the product specification.

2. SPECIFICATION LIST

The complexity of our specification system makes the intelligent selection of the "right" specification difficult and time-consuming. To simplify the retrieval of specification requirements the following list is provided.

2.1 RELIABILITY SPECIFICATIONS AND REFERENCES

These basic specifications, standards and references are utilized in procurement of systems and equipment, to obtain required reliability.

MIL STD 785 - Reliability management of Department of Defense Military Systems: This standard was developed to provide industry with guidelines and procedures necessary for establishing and implementing reliability programs on military systems. When invoked it requires the contractor to establish and maintain an effective and economical reliability assurance program, adjusted to suit the type and phase of the procurement. See section 3.2 below.

MIL STD 441 - Reliability of Military Electronics Equipment: This standard was developed to establish a procedure for the development and design of electronics equipment to insure required inherent reliability. It gives a very general statement of design principles and considerations to be applied.

MIL R 22732 - Reliability Requirement for Shipboard and Ground Electronic Equipment: This specification prescribes the procedures for management of reliability assurance programs in the development of shipboard and ground electronic equipment. When invoked, it requires (a) knowledge of and application of principles of design for reliability; (b) establishment of a reliability assurance program; (c) verification of achieved reliability by testing as specified in the individual equipment specification, or as proposed by the contractor if not specified; (d) provides an alternate verification procedure by analysis and prediction, when approved by the Bureau, when demonstration testing is impossible or impractical. See section 3.2 below.

MIL STD 721 - Provides general definitions of terms for reliability engineering.

MIL STD 756 - Reliability Prediction - Provides general prediction procedure based on parts failure rates, with chart for electronic "active elements".

MIL STD 105 - Provides sampling procedures and tables for inspection by attributes. This standard, with Technical Report

#10, ONR (Contract NONR-401(143)), "Factors and Procedures for applying The MIL STD 105D Plans In Life and Reliability Inspection" may be used to design life and Reliability testing and demonstration plans.

MIL HDBK 217 - Reliability Stress and Failure Rate Data.

MIL HDBK H108 - Sampling Procedures for Reliability testing.
MIL STD 781 - Demonstration plans for Reliability.
NAVSHIPS 93820 - Handbook for the Prediction of Shipboard and Shore Electronic Equipment Reliability.

NAVSHIPS 94501 - Bureau of Ships Reliability Design Handbook.

MIL STD 839(USAF) - Parts, with established reliability levels.

2.2 MAINTAINABILITY SPECIFICATIONS AND REFERENCES

These basic specifications, standards, and refernces are utilized in procurement of systems and equipment to obtain required maintainability and availability.:

MIL M 23313 - This specification was developed to prescribe maintainability program requirements in the development of shipboard and shore electronic equipment. When invoked it requires the contractor to (a) establish a maintainability assurance program, (b) apply maintainability criteria in the design, and (c) report and evaluation of the achieved maintainability.

MIL STD 778 - Provides general definitions for maintainability engineering.

MIL M 19562 - Provides instructions for the preparation of Maintenance Prints for Electronic Equipment.

NAVSHIPS 94324 - Maintainability Design Criteria Handbook for Designers of Shipboard Electronic Equipment.

Maintainability Prediction Procedure for designers of Shipboard Electronic equipment and systems. Report by Federal Electric Corporation, Contract NOBSR 75376.

2.3 GENERAL SPECIFICATIONS AND REFERENCES

These basic specifications, standards and references, while they are not primarily concerned with reliability and maintainability, are utilized with significant impact on reliability and maintainability:

MIL E 16400 - Electronic Equipment, Naval Ship and Shore, General Specification: This specification (a) defines a basic design philosophy in development of Naval Electronics Equipment of utilizing the latest construction techniques with the objective of increasing reliability, making equipment easier to maintain and reducing overall cost, (b) invokes MIL R 22732B which requires a reliability assurance program, including verification of reliability, when specified in the individual equipment specification. See section 3.1 below.

MIL STD 202 - Describes test methods, including environmental and overstress methods for the testing of Electronic and Electrical components.

MIL STD 210 - Provides reference for probable climatic conditions of the natural environment to which Military Equipment may be exposed.

MIL STD 242 - Electronic Equipment parts (selected standards): Provides standard dimensions, ratings, etc. Selection of parts from this compilation does not constitute parts control in the reliability sense.

MIL STD 446 - Establishes uniform environmental design requirements for use in development and procurement of Electronic Parts, tubes and solid state devices.

Suggestions for designers of Electronic Equipment (Booklet prepared by USNEL).

MIL STD 803 (USAF) - Human engineering criteria for aircraft, missile, and space systems, ground support equipment.

2.4 SPECIFICATION CHART

Figures 17-9, 17-10 and 17-11 provide some perspective of the variety of tasks covered by reliability and maintainability specs, and the differences of emphasis across various military and NASA agencies. Although chapters 22 and 23 contain the recommended specification language, the BuShips engineer should be familiar with these other specifications that may contain language useful for specific situations.

R & M SPECIFICATIONS

SUBJECT	RELIABILITY						MAINTAINABILITY		
	DOD	NAVY			USAF	NASA	NAVY		USAF
	MIL STD 785	MIL R 22732	MIL STD 441	BuWeps WS-3250	MIL R 27542A	NPC 250-1	MIL M 23313	XWR-30	MIL M 26512B
Organization - Responsibility & Authority	3.1, 3.3.2, 3.3.3	-0-	-0-	3.2.f, 3.3, 3.5.1, 6.5.1, 6.5.9	3.3.2, 3.3.3, 3.4	2.1	-0-	-0-	3.2.3.1
Program Plan & Budget	3.1, 3.3.3	1.2, 1.2.1, 1.2.2, 3.3	-0-	3.2,3.4, 3.5.lb, 4.3.2	3.1, 3.3.3, 3.5	2.2.1, 2.2.2, 2.2.3, 2.2.4, 2.3.2.4	3.1.1	Pts II-2 II-3	3.2, 3.2.1, 3.2.3.1
Customer Requirements Study	3.2	1.2,3.2, 3.2.1, 3.3.1, 3.3.2, 3.4.3.2, 3.4.4	1.3.1, 1.3.2, 3.1.1, 3.1.2	3.1,3.4, 4.1,4.2	3.2	1.3, 1.4.1, 1.4.2, 1.5, 1.6.1, 1.6.2	3.1.1.1, 3.1.1.2, 3.1.1.3, 3.2, 3.2.1, 3.2.2, 3.2.3, 3.3.1, 3.3.2, 3.3.3, 3.3.4	Pts I-1, I-2, II-4, II-5, II-6, II-7, III-1-1, III-1-2, III-1-3, III-2-1, IV-1-2, V (all) Exh III, V, VI	3.1.1, 3.1.2, 3.1.3, 3.1.4, 3.2, 3.2.2.1

R & M SPECIFICATIONS

SUBJECT	RELIABILITY						MAINTAINABILITY		
	DOD	NAVY			USAF	NASA	NAVY		USAF
	MIL STD 785	MIL R 22732	MIL STD 441	BuWeps WS-3250	MIL R 27542A	NPC 250-1	MIL M 23313	XWR-30	MIL M 26512B
Design Analysis - Predictions & Design Reviews	3.3.1, 3.3.3, 3.5.1, 3.5.4, 3.5.5, 3.5.6, 3.5.9, 3.5.11	3.4, 3.4.1, 3.4.2, 3.4.3	3.1.3.4, 3.1.4, 3.1.4.1	3.2.a, 3.2.e(2) 6 5.2	3.2.2, 3.5.1, 3.5.2, 3.5.4, 3.5.7, 3.5.9, 3.5.10, 3.5.11.5	3.1,3.2, 3.3,3.4, 3.5, 3.6.1, 3.6.2, 4.4,4.5	4.3, 4.3.1, 4.5	Pts III-1-4, III-1-6, III-1-7, III-1-8, Exh IV, App A-1, 2,3,4	3.1.3, 3.1.4, 3.2.2.2, 3.2.3.2
Parts Selection & Development Program	3.5.1.2, 3.5.3, 3.5.4	3.4.3, 3.4.3.1, 3.4.3.1.1	3.2.1, 3.2.2, 3.2.1, 3.2.9	-0-	3.4.3	3.9, 3.9.1, 3.9.2, 3.9.3, 3.9.4, 3.9.5, 3.9.6	-0-	-0-	-0-
Supplier Controls	3.5.7	-0-	-0-	3.2(c), 6.5.4	3.5.5	2.6.1, 2.6.2, 2.6.3, 2.6.4, 3.6.2	-0-	Pts VI-1-4, VI-2-2, VI-2-6	3.2.4
Fabrication & Assembly Controls	3.5.14	-0-	3.2.7, 3.2.8	3.2(b)	3.5.11, 3.5.12	3.8	3.3.4	-0-	-0-
Development & Environmental Testing (Qualification Testing)	3.5.1	4.3.2.1, 4.3.2.2	3.2.8, 3.2.4.2, 3.2.4.3, 3.2.4.4, 3.2.4.5 & Subs	-0-	3.5.1	4.1,4.2, 4.3.1, 4.3.2, 4.3.3	4.4, 4.4.1	-0-	-0-

R & M SPECIFICATIONS

SUBJECT	RELIABILITY						MAINTAINABILITY		
	DOD	NAVY			USAF	NASA	NAVY		USAF
	MIL STD 785	MIL R 22732	MIL STD 441	BuWeps WS-3250	MIL R 27512A	NPC 250-1	MIL M 23313	XWR-30	MIL M 26512B
Demonstration Testing	3.5.1.6	4.3	-0-	3.2(d) 6.5.6	3.5.13	4.3.4, 4.4	3.1.1.3	Pts III-2-1, III-2-2, III-2-3	3.2.2.3, 30.2, 40.1, 40.2
Acceptance Testing (Receiving Inspection)	-0-	4.5	-0-	3.5.2.b, 4.3, 4.3.1, 6.3.e, 6.6	4.1	-0-	6.5.1	-0-	-0-
Failure & Defect Analysis & Corrective Action	3.5.15	4.3.2.6, 4.3.2.8	-0-	3.2(f), 3.3(b), 6.5.8	3.5.12	3.7	3.5	-0-	40.1.1, 40.1.2, 40.1.3, 40.1.4
Data Submittal, Reports, Records & Procedures	-0-	3.4, 3.4.3.2	3.1.4, 3.2.9	2.1, 3.2.f, 3.3,3.5, 3.5.2	3.4, 3.5.3.2, 3.5.14	5.2.1, 5.2.2, 5.2.3, 5.3	3.4	Pts III-2-4, VIII	3.2.3.5.1 5.1, 6.1.1, 30.2
Training (Personnel Certifications)	-0-	3.3.1	-0-	-0-	3.5.6	2.5	3.1.1.1	Pts IV-1-1, IV-1-2, IV-1-3	3.2.3.1
Research-Analysis, Measurements & Control Methods	-0-	-0-	-0-	3.2.e(1)	-0-	-0-	-0-	-0-	-0-
Control of GFP	-0-	-0-	-0-	-0-	-0-	2.7	-0-	-0-	-0-
Change Control	-0-	3.4.2, 3.4.3, 4.3.2.8	-0-	3.2.e(3)	3.5.11.5	3.6.3	-0-	Pts VII-1-1, VII-2-1	3.2.7
Calibration	-0-	4.3.1.1	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Pack., Hdlg., & Shpg.	3.5.12	-0-	-0-	-0-	5.1	-0-	-0-	-0-	50.1

3. SPECIFICATION ABSTRACTS

3.1 GENERAL SPECIFICATION ABSTRACTS

In the procurement of an electronic systems specification MIL E 16400 (Navy) General Specification for Electronic Systems is usually invoked. The specification clauses relating to Reliability are abstracted herewith, showing the 16400E section number in parentheses:

(1.1) Scope. - This specification covers the general requirements applicable to the design and construction of electronic equipment and associated and auxiliary electronic apparatus furnished as part of a complete system intended for Naval ship or shore applications. The intent of this specification is to set forth the ambient conditions within which equipment must operate satisfactorily and reliably; the general material, the process for selection and application of parts, and to detail the means by which equipment as a whole will be tested to determine whether it will so operate. Throughout the design and manufacture of the equipment, maximum effort shall be made to attain the basic design objectives in that the equipment will meet the needs of the Naval service. Requirements applicable to individual equipments shall be as specified in the individual equipment specification.

(1.1.1) Basic design philosophy. - The design philosophy of Naval electronic equipment is to utilize the latest construction techniques with the objective of increasing reliability, making the equipment easier to maintain and to reduce overall cost. Manufacturers are encouraged to forward to cognizant bureaus, ideas, proposals and suggestions that will result in the foregoing objective. Details of this basic design philosophy are contained in applicable paragraphs of this specification. In addition, the complexity of modern electronics systems and the close relationship between the design of the equipment and the design of the ship make a closer liaison between the shipbuilder and the equipment manufacturer desirable. Even informal information which is timely, but not completely firm is often of great mutual value. The Navy encourages the early exchange of informal information between shipbuilders and equipment manufacturers.

(3.1) Design Objectives. - The basic design objectives are that the equipment will meet the needs of the Naval service and that the final product will reflect the utmost in simplicity, have maximum reliability consistent with the state of the art, and be easy to install and maintain.

(3.1.2) Reliability - Equipment reliability studies continue to verify that the majority of equipment failures can be traced to the improper selection and application of the electronic parts. To assure that the equipment will meet the requirements of Naval service, it is imperative that reliability of operation be considered of prime importance in the design and manufacture of the equipment. The contractor shall employ all methods possible in the process of manufacture which will assure quality and maximum reliability consistent with the state of the art.

(3.1.2.3) For Bureau of Ships equipment, quantitative reliability requirements, in terms of Mean Time Between Failures (MTBF), shall be that specified in the individual equipment specification in accordance with Specification MIL R 22732.

(3.1.2.3.1) A Bureau of Ships reliability assurance program, which shall include the verification of reliability requirements shall be established and maintained when specified in the individual equipment specification employing MIL R 22732 to the extent applicable.

(3.1.4) Ease of installation and maintenance. -

(3.1.4.1) Bureau of Ships. - The equipment shall be designed so that it can be easily installed and maintained. Maximum use shall be made of the design guides in NAVSHIPS 94324. Fault location accessibility and serviceability features which will lead to simplified maintenance shall be a prime consideration in the design (see 3.10.3 and 3.11.10).

(3.1.8) Failure reporting. - During research and development and service test evaluation of electronic equipment performed by the contractor, prior to Government acceptance, the following reporting is required:

(a) Each failure occurrence in which a part replacement is involved shall be reported and forwarded to the bureau or agency concerned using Bureau of Ships form "Electronic Equipment Failure/Replacement Report DD-787 (Proposed) BuShips Report No. 10550-1.

(b) An electronic equipment operating time log report shall be completed and forwarded to the bureau of agency concerned each month or upon completion of a specified test, whichever is shorter using "Elcctronic Equipment Operational Time Log, NAVSHIPS 4855" reporting form."

(6.4.2) Individual equipment specification. - An individual equipment specification is the detail specification covering a particular equipment.

(3.4.1) Selection of parts. - All parts used in the construction of Navy electronic equipment shall be in accordance with the requirements specified herein. The selection of parts in accordance with the following order is mandatory:

(a) MIL STD 242.

(b) Other Standards, Specifications and requirements listed herein but not included in MIL STD 242.

(c) MIL STD 143.

All parts used except as covered in (a) and (b) will require written approval in accordance with 3.4.1.2. Approval will not be granted for the use of parts of special or novel design, except as provided for in 3.4.5, where parts specified herein are suitable and available. This restriction shall not be construed as restricting the use of new or improved parts which will enhance the overall equipment reliability.

(3.4.1.1) Standard parts. - Standard parts are those parts specified in:

(a) MIL STD 242.

(b) Other standards, specifications and requirements listed herein (where no selected standard has been established in MIL STD 242 for that standard, specification or requirement).

(3.4.1.2) Nonstandard parts. - Action of the approval of nonstandard parts shall be in accordance with MIL STD 749. Tubes, diodes and transistors are considered as parts (see MIL STD 749). Written approval or disapproval of parts will normally be taken within 60 days after requires is received by the Bureau or agency concerned.

(3.4.2) Design Application. - Parameters, such as nominal ratings, tolerances, deratings, ambient temperatures, overload conditions, and the like, specified in individual part specifications shall be applied when using the parts. Where the parts used are not described by Military specifications, limits set as a result of Government Laboratory tests establishing specific suitability for Naval service shall not be exceeded. Particular attention is directed to the requirements for judicious choice of parts such that ratings, tolerances, and effects on circuit parameters after prolonged use are carefully considered. Specifically, deterioration due to permanent and substantial change of value(s) of a given part after aging is one of the prime causes of parts failure and circuit malfunctioning (see 6.6). Attention is also directed to the necessity for considering the possible degradation caused by temperature due to the nonjudicious choice of parts location. It is obviously undesirable to place many parts in the vicinity of items generating substantial heat, such as transformers and tubes. Attention should be directed to the cooling of cylindrically shaped parts by use of "chimmey effect" by mounting in a vertical plane. Where parts are stacked, the heat gradient and subsequent "hot spot" of the upper stack(s) should be given careful consideration.

(3.6.6) Fasteners and assembly screws. - All external fasteners and assembly screws which are manipulated, loosened, or removed in normal processes of installation and maintenance of equipment shall be of such as to provide strong contrast with the color of the surface upon which they appear. Other external fasteners and assembly screws shall be of the same color as the surface upon which they appear. Metallic couples which will cause galvanic corrosion shall not be employed to obtain contrasting color for Bureau of Ships contracts only.

(3.9.2) Preferred circuits. - In the interests of standardization of circuits, use of the standard preferred parts, and ultimately, the collection of circuit performance reliability data, circuits shall be selected from Standard MIL STD 439, where applicable.

(3.11.10) Accessibility. - The arrangement of parts shall be such that replacement or adjustment of any part is possible without removal of or damage to adjacent parts. All parts shall be readily accessible for replacement or repair.

(3.13.4) Arrangement. - Controls shall be so arranged as to facilitate smooth and rapid manipulation. Indicators shall be designed and arranged to insure readability under service conditions. Locations of similar controls and indicators on different panels shall correspond insofar as practicable.

(3.13.13) Time meters. - Time meters shall be provided for electronic equipment to indicate elapsed time for both stand-by and operation. The circuits to be monitored shall be as specified in the individual equipment specification.

(3.14.4) Parts identification by reference designations (symbol designations). - In order to facilitate maintenance, each part assembled in a major unit and set shall be identified by an appropriate reference designation in accordance with Standard MIL STD 16.

(4.1.1) Quality control system. - The contractor shall provide and maintain a quality control system acceptable to the Government for the supplies covered by the contract. The system of quality control shall be in accordance with MIL Q 9858. The procedures outlined in MIL Q 9858 shall serve to supplement and implement the design, performance and test requirements of the individual equipment specification.

(4.3) Preproduction inspection. - Preproduction inspection shall consist of all examination and testing necessary to determine compliance with the requirements of the individual equipment specification and unless otherwise specified therein shall include the examination and tests specified hereinafter. Where preproduction inspection has been made on an earlier model, a careful check shall be made to determine that all corrective measures found necessary as a result of such inspection have been carried out. (For each of the following, the applicable spec section number is given).

Surface examination	Power
Operating test	Radio interference & radiation
Weights and dimensions	Frequency spectrum signature
Supply line voltage & frequency	Controls and control circuits
Water cooling	Accelerated life test
Heat test	Shock, vibration, & inclination
Enclosure test	Salt spray test
Temperature	Reliability
Humidity	

(4.4.3) Production control inspection. - Production control inspection shall be conducted on a sampling basis and shall encompass functional and performance tests throughout the required range; tests which will detect any deterioration of the design by wear of such items as dies, molds, and jogs, and by substitution of different parts; tests which detect deviations in the processing of the materials; tests to determine temperature rise produced in operation and ability of equipment to withstand this heat; tests of efficiency; and tests of the performance with other equipment in a system. These tests shall be performed on the complete equipment as offered for delivery. Unless otherwise specified in the individual equipment specification, production control, inspection shall include the following (again section numbers are given):

- Weights and dimensions
- Supply line voltage & frequency
- Water cooling
- Heat test
- Enclosure
- Power
- Radio interference & radiation
- Equipment freq. spectrum signature
- Controls & control circuits
- Weld Test (when required)
- Reliability

(4.4.4) Environmental tests. - Environmental tests shall be conducted to prove the durability of the materials, parts, major units, and the equipment as a whole; life tests; simulated service tests; tests of the effects of changes of environment (such as extremes of temperature and humidity, effect of salt air); and tests of the effects of shock, vibration, inclination, and hard usage. Unless otherwise specified in the individual equipment specification, these tests shall include the following (again section numbers are given):

- Temperature
- Humidity
- Accelerated life test
- Shock, vibration and inclination
- Salt spray test

(4.5.13) Accelerated life tests. - If the equipment is designed for water cooling, these tests shall be conducted with water at $35^{o} \pm 2^{o}C$. inlet temperature continuously circulating through the water circuit. The equipment shall be subjected to the following conditioning and tests.

(4.5.13.2.2) The test cycle specified in 4.5.13.2.1 shall be repeated without interruption for a period of 360 hours (15 complete days).

(4.5.14.2.5) Test data. - Test data accumulated during the accelerated life tests, including details of all failures, shall be provided and shall be included in the report on preproduction inspection.

(4.5.17) Reliability. - Verification of reliability requirements shall be performed as specified in the individual equipment specification employing Specification MIL R 22732 to the extent applicable.

(6.2) Since this specification is general in scope and covers only the construction practices and the conditions under which equipment for Naval ship or shore use must operate, the details of performance of the equipment under the conditions stated herein and the ordering information must be specified elsewhere. Attention of design engineers is invited to the items listed below which should be covered in the individual equipment specifications.

a) Detail performance requirements for the particular equipment.

b) Class of equipment (see 1.2 and 3.8.1).

ff) Modification of production control inspection (see 4.4.3).

gg) Modification to environmental tests (see 4.4.4).

kk) Nominal conditions for accelerated life test (see 4.5.14.1.1).

c) Mean time between failures (see 3.1.2.3).

(6.5) This specification should be referenced in all individual equipment specifications, including specifications for equipment in the development stage, in order to insure the use of standard parts rather than nonstandard or special parts.

(6.6) The high reliability requirement becomes a critical problem with increasing complexity of equipment in terms of greater number of parts. Even part failure rates in the very low percent level, when multiplied by a large number of parts, present a high probability of equipment failure. Increasing availability of miniaturization techniques, of new high-reliability parts and new assembly methods will lead to space and weight savings. In each case, consideration shall be given to the use of weight and space savings for ultra-conservative design in critical circuits or the use of redundant circuitry in these areas. Redundancy techniques shall be considered only when it becomes evident from analysis of the tentative design that the high reliability requirements cannot be met in any manner.

(6.9) The NEL Reliability Design Handbook is cited as a design guide. Though very useful as a design guide, the applicable specifications under the specific contract shall govern in all cases of discrepancy, deviation or conflict between these contract specifications and this design guide document. All deviations from specification requirements under a contract shall be approved by the Bureau or agency concerned.

(6.9.2) An additional guide for designers is the booklet titled "Suggestions for Designers of Electronic Equipment". This booklet also references MN-8681B, "Vibration Problems in the Design of Shipboard Electronic Equipment". This is a 35mm sound movie, 16 minutes in length, which may be borrowed from any Navy district film library, Bureau of Ships and U. S. Navy Electronics Laboratory (USNEL), San Diego 52, California. The booklet may be obtained free of cost from USNEL.

3.2 RELIABILITY SPECIFICATION ABSTRACTS

Specification sections of MIL STD 785 and MIL R 22732B relating to a common objective are grouped together in this section, for comparison and used in procurement. Again, the specification section numbers are in parentheses:

Note that there is much duplication of intent, using different words for the same or closely related objectives. For example, quantitative requirements are called out by 3.2.1 (3.2.1) below, as well as 3.1 (3.1.2.3) above. Parts control is specified in 3.2.6 below, also in 3.1 (3.4.1 above). Verification is covered in 3.2.2 below and in 3.1 (4.4.4) and (4.5.18) above. However these are quite gross relationships. It has been found impractical to actually compare paragraph details. Chapters 22 and 23 do extract all parts of MIL STD 785 by actual contractor task, which sometimes involves extraction of a single sentence from a wide-ranging paragraph.

3.2.1 Quantitative Requirements

MIL STD 785 (3.2.1) Quantitative Requirements. The system reliability objectives and minimum acceptable requirements shall be as specified contractually. The minimum acceptable reliability requirements for some major subsystems and equipments may be included in appropriate sections of the system specification. The values not established by the procuring activity shall be established by the system contractor at a contractually specified control point prior to release of design for initial fabrication of specified articles.

MIL R 22732B (3.1) Detail requirements for individual equipments: Detail reliability requirements or exceptions applicable to particular equipments shall be specified in the individual equipment specification. In the event of any conflict between requirements of this specification and the individual equipment specification, the latter shall govern.

3.2.2 Reliability Verification: MIL STD 785 requires the contractor to develop a plan for demonstrating achieved reliability at specified milestones. MIL R 22732 gives detailed test requirements (based on AGREE plan) that tests the required reliability against an alternate hypothesis of 2/3 the required value with consumers and producers risks of 10%, (see chapter 11). This is not equivalent to demonstration of the required reliability. It actually demonstrates that the reliability is at least 2/3 of that required with 90% confidence. In the event the Bureau decides to use some test plan other than the AGREE plan, and particularly if a new one is prepared, it would be well to have the plan checked by a statistician.

MIL STD 785 (3.5.1) Test Requirements for Development Qualification and Acceptance: A planned and scheduled program of functional and environmental testing of equipment shall be conducted during design and development phases to estimate achieved reliability and to provide feedback of data as a basis for making reliability improvements. The development testing program shall confirm adequacy of selection of components and parts, determine capabilities and safety margins, evaluate drifts of component parameters with time, and determine failure-modes and relative failure-rates. If such data are not available, all items of the system determined by the reliability studies (3.2.2 and 3.3.3) to have a significant bearing on inherent reliability shall be tested early in the development program, unless other valid proof of adequacy can be presented.

(3.5.1.1) Environmental Requirements for Equipment Design and testing: If maximum environmental stress conditions have not been established by the procuring activity these shall be estimated from experience on past programs, and a test program for development, qualification, and acceptance shall be generated on this basis. Development and qualification tests shall be planned to evaluate the adequacy of design of equipment for the expected conditions in the use-environment (e.g., ground operation, launch, flight and orbit). The test plans shall include consideration of equipment, location, insulation shock-mounting, truss mounting etc. Environmental problem areas shall be identified at the system, subsystem, component and part level, and the effects of these problems on system reliability shall be estimated on equipments, components, or parts identified as critical. Detailed and specific review of environmental factors affecting reliability shall be performed. In addition to qualification and acceptance testing, additional testing shall be performed on critical items, such as life testing or failure-mode testing, to assess the affects of the environments on such critical items, and to determine adequacy of safety margins incorporated by system design, subject to approval by the procuring activity.

(3.5.1.2) Component Part Testing: All component parts to be used in production equipment shall be assigned a reliability index, failure-rate, or expected probability of failure under stated stress levels. The reliability test procedures of applicable military part specifications and testing specifications shall be used. Where the contractor deems these test procedures not applicable, he shall submit a justification of non-applicability and a description of the test procedures which he plans to use. A current record of the results shall be maintained. The test data shall be retained for a minimum period of 2 years from completion of contract. The test data shall be made available to information and data exchange activities upon request of the procuring activity.

(3.5.1.3) Maximum Pre-acceptance Operation: The contractor shall provide and maintain a current list of items having critically limited useful lives (total operating time or operating cycle) in their application. Derivation of maximum allowable operating time (or cycles of operation) shall be clearly defined with elements of data and methods of computations. The contractor shall propose for approval the time or number of equivalent operating cycles that is not to be exceeded prior to acceptance of the contractor's product. He shall ensure that each such item has its total operating time or number of equivalent operating cycles recorded, starting with and including its initial functional test, whether at the contractor's facility or a supplier's facility. Upon mutual agreement between the procuring activity and the contractor, any item may be dropped from the above list, or its limit revised, when changes in the items useful life indicate the need for such revisions.

(3.5.16) Reliability Demonstration

(3.5.16.1) Initial Plan: An initial plan for demonstration of achieved reliability at specified milestones, including estimated number of test articles and if not specified by the procuring activity a quantitative estimate of the confidence level, shall be prepared by the contractor and submitted in a section of the reliability program plan. The general plans for demonstration of reliability shall include trade-off curves showing number of test articles and operating test time or test effort versus confidence, and will encompass testing at the system major element level, and major subsystem or component levels separately and in combination.

(3.5.16.2) Final Plan: Final plan for demonstrating achieved reliability shall include any revisions to data in the initial plan, and the ground rules and conditions for deciding whether a test shall be classified as a success or failure, or shall be excluded due to invalid test data. Reliability demonstration plans shall apply all results of testing and operations from which valid reliability measurement or assessment can be obtained. Engineering tests and analyses, e.g., test to failure concepts, shall be included to supplement statistical measures. The milestones that are to constitute demonstration of contract compliance shall be established and incorporated in the contractual documents. Specific plans for conducting a reliability demonstration shall be submitted for approval at the time specified by the procuring activity.

(3.5.16.3) Test Plans: The test plans contained in MIL STD 781, when applicable, shall be applied.

MIL R 22732B (3.2.5) Prototype (pre-production) models: When the procurement includes the fabrication of prototype (pre-production) models of the equipment, the contractor shall perform a reliability demonstration test to assure that the reliability required in the individual equipment specification is characteristic of the equipment design.

(3.2.5.1) Reliability Demonstration: Reliability demonstration tests shall be performed in accordance with 4.2 and 4.3. Tested equipments shall exhibit a mean-time-between-failures (MTBF) equal to or greater than that specified in the individual equipment specification as determined by 4.2.6. No decision to accept or reject shall be made until each equipment tested has accumulated an operating time of at least 3/2 times the specified MTBF without specific approval by the Bureau or agency concerned. If the test terminates in a reject decision, the contractor shall indentify the cause or causes of such a decision from an analysis of the failure data accumulated during the test and propose corrective action necessary to eliminate the causes of unreliability identified. When it is impossible or impractical to require reliability demonstration and testing in accordance with 4.2 and, upon specific approval by the bureau or agency concerned, the reliability assurance procedure of paragraph 4.3 shall be applied.

(3.2.5.2) Reporting: The results of the reliability demonstration test shall be summarized in a report to the procurement agency. This report shall contain the records specified in 4.2.5 and an analysis of the information they contain.

(3.2.6) Production: When equipments are committed to production, the contractor shall perform reliability production tests on production units to demonstrate that the level of reliability required in the individual equipment specification is maintained during the production process.

(3.2.6.1) Reliability Production Tests: Reliability production tests shall be performed on samples taken from each periodic production lot in accordance with the criteria of 4.2. Unless otherwise specified in the individual equipment specification, the periodicity for reliability production testing shall be one month. Tested equipments shall exhibit a MTBF equal to or greater than that specified in the individual equipment specification as determined by the criteria of 4.2.6. No untested production units shall be released as acceptable for shipment until the reliability test for that production lot results in an accept decision without specific approval by the Bureau or agency concerned.

(3.2.6.2) Reporting: The results of each reliability production test shall be summarized in a report to the procurement agency. This report shall contain the records specified in 4.2.5 and an analysis of the information they contain.

(4.2) Reliability Assurance by Testing:

(4.2.1) Reliability Tests: Reliability tests shall be conducted on samples of the prototype and production units of equipments that have minimum or specified MTBF requirements. If a specific reliability test plan is not indicated in the individual equipment specification, then 60 days prior to testing, the contractor shall submit for approval a detailed reliability test plan that incorporates at least the features specified by this document and by the individual equipment specification. Task Group Reports 2 and 3 of Reliability of Military Electronic Equipment may be used as a guide for completing the detailed test plan. Plans for reliability tests integrated with other quality conformance inspection tests may be submitted for approval to the bureau or agency concerned.

(4.2.1.1) Test Details: The contractor and the procuring group shall reach a written agreement specifying all aspects of the reliability tests, including reporting, forms before starting the tests. Rules for scoring failures shall be exact. The performance characteristics to be measured and their tolerances shall be covered in the individual equipment specification. They shall be kept to a minimum compatible with determination of satisfactory and unsatisfactory performance. The environment in which the equipment is tested, any preventive maintenance to be permitted, and other details of the test program shall all be submitted to the procuring activity and approved before the tests begin. When approved by the procuring activity, the contractor may elect to include any or all quality conformance inspection tests specified into the individual equipment specification or MIL E 16400 as part of the reliability test with no change in accept-reject criteria.

(4.2.2) Sample Size: The number of samples to be tested will be specified in the individual equipment specification. When not specified, the contractor shall propose a sampling plan for approval by the procuring activity.

(4.2.3) Environment: The following test levels shall be used for determining the environment to be imposed during reliability testing; the selection of the particular guide shall be specified in the individual equipment specification.

(4.2.5) Recorded Data: From the start to the conclusion of the test, the contractor shall maintain a continuous adequate and accurate record of measurements of performance, test time, test operator's observation, failures, and test facility conditions. The data taken during the test shall be the least necessary to complete the following: (a) Operational sheet; (b) Log of equipment failures and operating time; (c) Failure report; (d) Equipment logs.

(4.2.5.1) Operation Sheet: The operation sheet shall be designed to provide a continuous record of the test sample and test facility performance.

(4.2.5.2) Log of equipment failures and operating time: The log of equipment failures and operating time shall contain the information necessary for an accept or reject decision. The heading of the log shall identify the test, the specific equipments under test, and the person responsible for the log. The body shall contain the following information: (a) Entry number; (b) Date and time of entry; (c) Identification of equipment that failed; (d) Accumulated operating time of all equipments; (f) Normalized test time (item (e) divided by specified MTBF); (g) Total number of failures observed for all equipments on test.

An entry shall be made at the occurence of each apparent equipment failure. If failure diagnosis reveals that the test speciment was not at fault, the failure may be deleted upon appropriate reference to the operation sheet. Upon accumulation of enough time or failures for either an accept or reject, the test shall be concluded with an appropriate entry.

(4.2.5.3) Failure Report: Completion of a failure report to sufficiently describe all pertinent circumstances attendant to each equipment failure shall be mandatory. The failure report shall have two main parts; one shall report the exact nature of the failure, and the other shall report the cause to the fullest extent possible. The first part shall describe the symptoms and the diagnosis action taken, how the equipment was repaired, identification of parts replaced or adjustments made, and what the effect of the repair was. The second part shall include an analysis of the failed part, an analysis of the circuit, and proposals for action to prevent recurrence of the failure.

(4.2.5.4) Equipment Log: There shall be an equipment log for each unit tested. It shall remain attached to the unit throughout the test to provide a complete history of the equipment. The equipment log shall report the performance of the equipment, any adjustments or repairs, and the operating time accumulated during the reliability test.

3.2.3 Planning Tasks: MIL STD 785 (paragraph 3.1) provides a clear statement of requirements for the contractor to conduct his work on the contract in a logical orderly manner. It is particularly applicable to CPFF contracts, when it can be administered, where it can be a very useful tool in obtaining visibility of the contractor's performance. MIL R 22732, while requiring that the contractor have a program, does not require its documentation and hence limits visibility and control over adequacy of planning.

MIL STD 785 (3.1) Reliability Assurance Program: The contractor shall establish and maintain an effective and economical reliability assurance program, planned, integrated, and developed in conjunction with other planning functions. The program shall be adjusted to suit the type and phase (design, development, production) of the procurement. The program shall be based upon the severity of the requirements, the complexity of the design, the quantity under procurement, and the manufacturing techniques required. The program shall assure adequate reliability consideration throughout all aspects of the design, development, or production as necessary to meet the contractual reliability requirements.

(3.3.1) Proposed Reliability Program Plan: The contractor's proposed reliability program plan, in accordance with the requirements of the work statement and this standard, shall be submitted as a separate and complete entity within the contractor's proposal for the system. The proposed plan must be an integrated effort within the total program plan; it shall provide specific information as to how the contractor will meet specified quantitative reliability requirements during development and manufacture including the design concepts to be utilized. The proper manner of demonstrating reliability at stated confidence levels shall be described. The proposed reliability program plan, as approved by the procuring activity will become a contract compliance document; reliability test plans must be an integral part of the program test plan.

(3.3.2) Reliability Organization: The program plan shall (1) identify the organization and the personnel responsible for managing the overall reliability program, and (2) shall clearly define its responsibilities and functions including both policy and action. It shall stipulate the authority delegated to this organization to enforce its policies. The relationships between line, service, staff, and policy organizations shall be identified.

(3.3.3) Management and Control: The program plan shall include detailed listing of specific tasks, man-loading per task, and procedures to implement and control these tasks. It shall include a description of each task to be performed whether or not it is already documented in contractor directives, the organizational unit with the authority and responsibility for executing each task, the method of control to insure executive of each task as planned, and scheduled start and completion dates of each task. This data shall be in a form that permits technical auditing by the procuring activity. The information provided shall include the method of analysis to be used as a basis for achieving the proper balance of effort and resources from a reliability standpoint. The contractor shall identify specific technical problems to be solved, review problems considering program requirements, and develop a detailed program to solve the problems. Records shall be maintained on the status of actions to resolve problems. All designers and associated personnel shall be made aware of the reliability requirements pertaining to their area of responsibility and shall be included in the information loop to correct known deficiencies. The designation of milestones, definition of inter-relationships, and estimation of times required for reliability program activities and tasks shall be employed as part of overall program control which applies the program techniques. If PERT (Program Evaluation and Review Techniques) is part of the program it shall be utilized.

MIL-R-22732B (3.2) Reliability Assurance Program: The contractor shall establish and conduct a reliability assurance program including, as a minimum, the elements required by this specification. The contractor's reliability assurance program shall be consistent with the requirements of MIL-STD-441 and the requirements of this specification. Where the requirements of MIL-STD-441 and this specification conflict, the requirements of this specification shall govern. The fundamental features of the reliability assurance program shall be consistent with the extent to which the particular procurement embraces the procurement phases of feasibility study, design and development, prototype (preproduction) fabrication, and production. When these phases, either individually or collectively, are included in the procurement the reliability program elements listed thereunder are required.

3.2.4 Evaluation Tasks: The treatment afforded by MIL-R-22732 (paragraph 3.2.2 and 4.3) in the use of reliability analysis to improve the product while in the design stage is excellent. Reports are not specified in detail. The visibility would be improved by some elaboration of reporting requirements.

MIL-STD-785 (3.2.2) Reliability Requirement Studies: The reliability program shall procide for preliminary and continuing studies of reliability estimates and achievements. The reliability program for all program phases shall provide for progressive refinement of the reliability analysis and validation of specified requirements for all planned missions or operational modes of the system. These studies shall include definition of functional performance limits, duration of operation in time or cycles, etc., and the environmental conditions of operational use. Apportionment of reliability requirement from the system to system elements shall consider complexity and importance (effect of failure) of the system elements including alternative modes of operation. Progressive reliability goals shall be established for each major phase of a program which are phased with program review points (3.4).

(3.5.4) Critical Items: The contractor shall establish an effective method for identification, control and special handling of critical parts, components, subsystems or other end items from design through final acceptance. Such methods shall be described in the contractor's formal policies and procedures to assure awareness by all affected personnel (e.g., design, purchasing, manufacturing, inspection, test, handling, etc.) of the essential and critical nature of such items. The methodology used in generating the critical item list shall be furnished to the procuring activity. The method used and the list subsequently generated shall be subject to review and evaluation of the procuring activity.

(3.5.5) Mathematical Models: The contractor shall provide mathematical models based on systems analysis to apportion reliability over major systems elements; and to predict reliability at various stages of design. The mathematical models, apportionment, and initial prediction shall be included in the program plan

(3.5.9) Human Engineering: The reliability program shall apply the principles of human engineering in all operations during design development, manufacture, test, maintenance, and operation of the system or subsystem. The design shall incorporate human engineering features that minimize the possibility of degrading reliability through human error. Contractor's human engineering personnel shall participate in design activity and proposed tests to assure that the principles in MIL-STD-803 have been incorporated in design and are reflected in test plans.

(3.5.10) Statistical Methods: The contractor's reliability program shall incorporate optimum utilization of statistical planning and analysis. This shall include application of such methods as design of experiment, analysis of variance, and other methods applicable to design, development, and production phases.

(3.5.11) Maintainability: The effects of the reliability program on the maintainability of the design shall be considered during the initial and subsequent design phases to assure minimum degradation to system availability.

(3.5.12) Effects of Storage, Shelf-Life, Packaging, Transportation, Handling, and Maintenance: The contractor shall determ...

by test and analysis, or shall estimate, the effects of storage, shelf-life, packaging, transportation, handling and maintenance on the reliability of the product. He shall design the product to withstand these effects. Any special requirements or limitations on shelf-life, storage, packaging, transportation, handling, and maintenance shall be made known to the procuring activity.

MIL-R-22732B (3.2.1) Feasibility Studies: Reliability shall be considered in determining whether or not practical application of a concept or tentative design is possible for this purpose, an estimate of reliability shall be determined using the applicable method set forth in NAVSHIPS 93820 consistent with the extent to which the design configuration is known. The effect of the estimated reliability on other mission parameters of maintainability, availability, and effectiveness shall be analyzed and identified together with a description of the relationships between reliability and these parameters in achieving the intended mission objective.

(3.2.2) Design and Development: It shall be recognized by the contractor that the inherent reliability of any product is determined by the basic design which is the limiting factor in achieving high reliability during military use. Accordingly, the major emphasis by the contractor in attaining the degree of reliability required by the individual equipment specification must be applied during product design and development. In product design and development the following reliability program elements are required.

(3.2.2.1) Product Identification: The contractor shall identify the complete product involved in the procurement to which the numerical reliability requirement in the individual equipment specification applies. The mission objective shall be delineated together with the specific criteria for determining product success or failure. The numerical reliability requirement shall be interpreted by the contractor in terms of the mission objective, the product configuration, and the criteria for success and failure.

(3.2.2.2) Reliability Design Guides: The contractor and his personnel shall familiarize themselves with the Bureau of Ships Reliability Design handbook NAVSHIPS and make maximum use of the design guides therein in the design and design modifications required by the individual equipment specification as well as this specification.

(3.2.2.3) Mathematical Model: The contractor shall establish a mathematical model relating the reliability of the complete product to the design configuration, modes of operation, duty cycles, and reliability indexes used for evaluation. The mathematical model shall provide the basis for reliability prediction, analytical reliability assessment, and allocation of reliability goals to lower levels within the product.

(3.2.2.4) Allocation of Reliability Requirements: The contractor shall apportion the reliability requirement from the individual equipment specification to lower levels within the product by allocating numerical reliability goals to each subsystem, equipment, assembly, sub-assembly, down to each non-repairable part. When recombined in accordance with the mathematical model (see 3.2.2.3) the allocated goals shall yield a product reliability which equals or exceeds the requirement in the individual equipment specification. The detail goals shall provide the basis for establishing reliability criteria for suppliers products and for evaluating progress when compared with the results of subsequent reliability predictions and tests. Such comparisons shall serve as a means for detecting potential trouble areas and for adjusting reliability effort to areas where needed to meet required reliability levels.

(3.2.2.5) Initial Reliability Prediction: The contractor shall perform an initial reliability prediction for the complete product utilizing Method C set forth in NAVSHIPS 93820. Parts or subunits not covered by existing data in NAVSHIPS 93820 shall be identified and means for obtaining reliability figures of merit for these items shall be stated by the contractor. Use of reliability data from other sources such as parts suppliers or other reliability documentation is permissible subject to approval by the procuring agency, however, such data shall not take precedence over data for identical items contained in NAVSHIPS 93820 unless fully justified by the contractor and approved by the procuring agency. Correlation shall be made between allocated reliability goals (see 3.2.2.4) and reliability predictions.

(3.2.2.7) Final Reliability Prediction: The contractor shall perform a final reliability prediction incorporating all design changes made during the development process and representing the final design configuration to be used in the product Method D of NAVSHIPS 93820 shall be used together with data from other sources as required and substantiated, taking into account the failure characteristics of parts for which severity (stress) functions versus failure rate are known and documented. Correlation shall be made between allocated reliability goals (see 3.2.2.4) and the final reliability prediction.

(3.2.8) Qualitative Requirements: Equipments that do not have a specified minimum MTBF shall be designed and produced to attain the maximum practical MTBF. Such equipment shall be free of the known causes of poor reliability such as unnecessary complexity, misapplication of parts, marginal design, and poor workmanship. The reliability assurance procedure prescribed in 4.3 shall be applied to verify that the equipment fulfills this requirement.

(4.3) Reliability Assurance by Analysis and Prediction: The following procedure shall be applied to all electronic equipments regardless of whether quantitative reliability requirement are involved and regardless of whether reliability testing is required.

(a) The MTBF of the equipment shall be predicted using Method D of publication NAVSHIPS 93820.

(b) The design shall be reviewed and analyzed in detail by a group provided by the contractor independent of the designers to determine that it is inherently as reliable as is practical. It shall be the particular function of this group to constructively criticize such common weaknesses as unnecessary complexity, misapplication of parts, and those commonly called "marginal design". This group shall report the results of the design review and analysis together with recommendations to the procurement agency and the designers.

(c) Any failure of a prototype or preproduction equipment that occurs during the development, construction, or testing of the equipment shall be analyzed and reported to the procurement agency. The analysis shall be conducted in such a manner as to determine the cause of the failure so that its recurrence can be prevented. Reports of the failures and their analyses shall be forwarded to the design review group for endorsement.

The equipment shall be considered acceptable whenever the reliability prediction, the design review, and the failure analyses are completed and the procurement agency is satisfied that any faults revealed by these studies have been corrected.

3.2.5 Design Review:

MIL-STD-785 (3.5.6.1) Periodic design reviews for reliability and evaluation of designs shall be conducted as an integral part of the contractor's engineering design review and evaluation procedures. These reviews shall evaluate the achievement of reliability relative to the reliability goals established for each major phase and review point of the contract; with contractor evaluation before designs are finalized. The reliability design review analyses shall include, to the extent applicable:

(1) Reliability estimates based upon prediction (such as MIL-STD-756 and MIL-HDBK-217 as basic data) and accumulated test data. Estimates shall be made for each mode of operation.

(2) Review of potential design or production problem areas.

(3) Analysis of effects of failure.

(4) Identification of the principle, critical items inhibiting reliability achievement.

(5) The effects of engineering decisions and trade-offs upon reliability achievements, potential and growth.

(3.5.6.2) The program plan shall specify appropriate personnel from the contractor's reliability organizations who shall participate in the design reviews and denote approval by signature. These reviews shall be continuing in nature to provide for the earliest possible detection and correction of any potential deficiencies. A system shall be established and maintained by the contractor to assure reliability participation in control of designs, specifications, drawings, and all changes thereto.

(3.5.6.3) The design review shall compare the design with previously defined qualitative and quantitative requirements. The results of the review shall be documented.

(3.5.6.4) The procuring activity shall be notified at least 10 days prior to each scheduled formal design review (as distinguished from continuing), to permit procuring activity participation. The minutes of such reviews shall be made available to the procuring activity upon request.

MIL-R-22732B (3.2.2.6) Reliability Design Review: The contractor shall perform a reliability design review function conducted by experienced reliability personnel not directly subordinate to the design engineering function. The design review shall include a detailed examination of the design documents, drawings, and specifications and a complete evaluation of the effects of part selection and application on the reliability of the product. Evaluations shall include analysis of environmental stresses (temperature, humidity, vibration) as well as physical stresses (electrical, mechanical) sustained by parts during intended military use of the product. Identification shall be made of critical or marginal features of the product design which adversely affect reliability as determined by the design review. Provision s all be made by the contractor for approval by the reliability design review function prior to final release of the product design.

(3.2.3) Incompatibility of existing design and required reliability: In the event that incompatibility of existing design and required reliability is established, the contractor shall prepare and submit to the procuring activity for approval, a proposed program for accomplishing such design changes as are required to insure compatibility. Where possible, such design changes shall include at least, but shall not be limited to consideration of reduction of thermal and electrical stresses on the equipment part complement. When it is established that the required reliability level is not obtainable within the existing state of the art for parts, the contractor's proposal shall include a diagnosis of optimum types of and locations for redundant circuitry and the scope of the work necessary to provide the required reliability by these means.

3.2.6 Parts Reliability: MIL-STD-785 provides a very effective coverage of parts control. MIL-R-22732B does not cover this area. Where MIL-E-16400 is utilized in the procurement, the parts selection requirement requires selection of standard parts from MIL-STD-242. These parts are preferred on a basis of standardization rather than on a basis of high reliability and hence do not guarantee performance of the part.

MIL-STD-785 (3.5.3) Parts Reliability: Parts shall not be used without knowledge of their capabilities and reliability potential determined from current or previous testing. Information shall be sought or generated on stress levels and limits of application as well as on failure rate. Available data and central information facilities shall be utilized to avoid needless duplication of testing. In using existing data, the risk and limit-

[illegible] part performance data at one set of environments to that expected at a different set of environments shall be recognized and documented. The best available estimate or determination of failure rate for each part type shall be made; the part vendor's accumulated test history under part specifications requiring failure rate verification shall be sought. Reported measure of achieved reliability should not be based upon short duration tests which predominately measure performance. If time does not permit adequate testing at advanced ages, the contractor shall show the age range actually tested and shall justify use of such data.

(3.5.3.1) Where estimates, data, and experience indicate a need for a parts reliability improvement program to achieve desired system reliability, the contractor shall propose a program to increase the standardization and reliability of parts to the required level. A preferred parts list shall be maintained and utilized as a source of high reliability parts.

(3.5.3.2) Emergency Reporting of Defective Parts: When a MIL specification or a MIL part is deemed suspect by the development contractor, the contractor shall:

(a) Indicate reason with supporting evidence of this conclusion.

(b) Perform failed part diagnosis and analysis of those parts deemed suspect development, acceptance tests, and other related activities.

(c) Whenever possible, reach a conclusion relative to the cause of failure.

(d) Report by most expeditious means to the procuring activity with concise supporting data when, and only when, it has been concluded that a part is unsatisfactory for any of the following reasons:

(1) A part which was accepted as meeting a MIL specification but which failed to perform to expectations, such failure concluded to be attributable to: (a) Manufacturing procedures, choice of materials, or design of part, or (b) Test and inspection disciplines.

(2) A military part specification which is inadequate in that it (a) does not take advantage of the state-of-the-art, (b) requires amendment to encourage advance-

ment of the state-of-the-art; or (c) requires revision for clarity.

3.2.7 Supplier Control:

MIL-STD-785 (3.5.7) Supplier and Subcontractor Reliability Programs: The contractor shall be responsible for assuring that suppliers's and subcontractor's achieved reliability levels are consistent with overall system requirements. The contractor shall impose, directly or indirectly, quantitative reliability requirements and acceptance criteria on all echelons of suppliers and subcontractors; and shall incorporate applicable portions of this standard in subcontracts and purchase orders. The reliability program of the contractor shall contain provisions for surveillance of supplier and subcontractor reliability activities including failure reporting. The surveillance shall consist of but not be limited to such items as maintaining a supplier selection program based upon review of the supplier's reliability program, quality control system, examination of his facilities, and past performance, to assure that suppliers are capable of attaining and maintaining the required level of reliability. The contractor shall take all actions necessary to assure that no changes made by any supplier will reduce reliability of the system. Records of each supplier's performance shall be maintained and reviewed with him periodically.

3.2.8 Failure Data and Diagnosis: MIL-STD-785 provides for the collection of success/failure data and the analysis of failures occurring to the product or to the components before assembly. MIL-R-22732 requires recording of failures occurring during the reliability tests, with analysis and report of their causes.

MIL-STD-785 (3.5.15) Failure Data Collection, Analysis, and Corrective Action: (a) The contractor shall have and shall require major subcontractors to have a closed loop system for collecting, analyzing, and recording all failures that occur during phases of tests required for system elements including those that are performed in-plant and at installation sites. The contractor shall describe his failure reporting procedures, including flow charts, for the analysis, feedback and corrective action as part of the program plan (see 3.3.3). The contractor shall explain the method by which failure reports are initiated. Analysis and recording of failures shall differentiate between, but not be restricted to, those due to equipment failure and those due to human error in designing, processing, handling, transporting, storing, maintaining, and operating the equipment. Elapsed time indicators on event counters shall be utilized or a log shall be maintained to report accumulated operation time or operation cycles on system components that are time or operation cycle sensitive. The failure reporting system shall be designed to be compatible with the maintenance data collection system of the procuring or using activity so that, as the system nears the operational inventory phase, transistion to in-service failure reporting can be accomplished with the minimum disturbance and maximum continuity of effort. The failure reporting system shall include provisions to assure that effective corrective actions are taken on a timely basis to reduce or prevent repetition of the failures. The contractor shall establish scheduled audits to review all open reports, analyses, dates for corrective action and report all delinquencies to management.

(b) The contractor shall commence failure reporting with initial development testing or operation including operating equipment at receiving inspection, at a vendor's plant in final assembly check-out, or during acceptance testing. An unscheduled adjustment, other than a calibration made during other maintenance because of convenience, shall be defined as a failure for reporting purposes. Failures of components prior to incorporation into an assembly shall be recorded separately and reported.

(c) The contractor shall submit failure report summaries as specified by the procuring activity.

3.2.9 <u>Supporting Activities:</u>

<u>MIL-STD-785</u> (3.5.2) <u>Furnished Equipment:</u> Where other equipments, such as Government-furnished or associate contractor supplied equipment are to be integrated to provide a complete operational system, the contractor shall use known or estimated reliability values for these equipments. When such empirical data are not available through the channels to which the contractor has access, the contractor shall request such data from the procuring activity. The contractor shall report potential reliability problems introduced by deficient Government-furnished equipment or other associated equipment over which he has no control and shall indicate and justify the system changes necessary to accommodate or the improvement necessary to make this equipment compatible with the system requirements.

(3.5.8) <u>Reliability Indoctrination and Training:</u> The reliability program shall contain provisions to supplement the basic training and indoctrination of company and plant personnel with reliability training to assure that their skills and knowledge keep pace with advancing technology and the requirements or peculiarities of the system or equipment.

(3.5.14) Manufacturing Controls and Monitoring: The contractor shall have a planned, controlled and schedule system of production control and monitoring to assure that reliability achieved in design is maintained during production.

MIL-R-22732B (3.2.9) Support Activity: The contractor's facilities and organization shall be such as to insure that all support which affects equipment reliability will be accomplished in a manner compatible with the requirements of this specification. Such support shall include, but is not limited to, the following: (a) Quality control systems requirements in accordance with MIL-E-16400, and (b) Reliability indoctrination of personnel.

3.2.10 Monitoring and Review: MIL-STD-785 provides for the program to be reviewed at planned points. MIL-R-22732 requires progress reports monthly and at the conclusion of specific elements, (apportionment, prediction, design review and testing). The coverage in the progress report is not clearly specified, but the inference would seem to include the progress and results on the particular elements.

MIL-STD-785 (3.4) Program Review: The reliability program shall be organized and scheduled to permit the contractor and the procuring activity to review its status, including results achieved, at pre-planned steps or checkpoints. This formal review and assessment of reliability normally will be conducted at major program points and these points will be established by the procuring activity during negotiations. As the program develops, reliability progress shall be assessed by use of such information as predictions of reliability and results of reliability design reviews and tests including effects of human performance.

MIL-R-22732B(3.2.8.1) Reporting: The results of the reliability assurance plan shall be summarized in a report to the procurement agency. This report shall include the results of the reliability prediction, design review, and failure analyses specified in 4.3 together with a discussion of the information contained therein.

(3.2.4) As a minimum, reports shall be submitted 45 days after award of contract and monthly thereafter to end of contract, or at the conclusion of each program element specified in 3.2.2.1, 3.2.2.3, 3.2.2.4, 3.2.2.5, 3.2.2.6, 3.2.2.7, 3.2.5.2, 3.2.6.2, and 3.2.8.1 whichever occurs more frequently.

3.3 MAINTAINABILITY SPECIFICATION ABSTRACTS

There is considerable overlap between maintainability and reliability specifications, the prime example being design review. Most such specifications read as though separate design review meetings are required for maintainability, reliability, safety, and the host of other important design considerations. To the contractor this is not economical or relaistic, since trade-offs between these disciplines are involved. For this reason Chapters 22 and 23 recommend language that combines the discipline where it is appropriate.

For electronic systems, MIL-M-23313 provides a useful basic specification for obtaining a required MTTR in the product. This specification is not referenced in the general electronic system specification MIL-E-16400, nor in MIL-R-22732. To apply MIL-M-23313 to a particular procurement requires (a) reference to MIL-M-23313 in the procurement document, and (b) assignment of quantitative requirements.

There is no BuShip specification or MIL-STD released for maintainability requirements on systems other than electronic. To approach maintainability in such systems, the specific clauses must be developed in the procurement documents. In building up such a specification, (a) the numerical requirement must be specified, (b) the relevant factors of maintenance philosophy, replacement level of parts or components, and software support must be provided, (c) maintainability studies, design review effort, predictions and apportionment and special logistics studies, should be required, (d) details and frequency of reporting should be outlined, and (e) the acceptance test plan should be defined.

There is considerable variation between the approaches of the various services in attempting to obtain a specified maintainability of procured equipment. In addition to the Bureau's specification for maintainability requirements for electronic equipment and systems, selected abstracts of Air Force and Bureau of Naval Weapons are furnished for clarification of understanding.

3.3.1 MIL-M-23313A (SHIPS) - Maintainability Requirements for Shipboard and Shore Electronic Equipments and Systems.

(1.1) This specification covers maintainability requirements for Bureau of Ships shipboard and shore electronic equipment and systems.

(1.2) In addition, this specification prescribes procedures to be followed for evaluation of equipment maintainability during equipment or system development and production programs. In particular it provides procedures for:

(a) Maintainability evaluation of final design.

(b) Preproduction maintainability test.

(c) Maintainability design review during production.

(d) Maintainability evaluation during preliminary design.

(3.1.1) Maintainability assurance program. - The contractor's (supplier's) maintainability assurance program shall be consistent with the requirements of this specification. The procuring activity will, at its option, review and evaluate the contractor's maintainability assurance program to determine whether or not it is adequate and consistent with the provisions of this specification. The maintainability assurance program shall include, but shall not be limited to, the following requirements or applicable portions thereof.

(3.1.1.1) Support activity. - The contractor's facilities or those of a subcontractor shall be such as to insure that all support which affects equipment maintainability will be accomplished in a manner compatible with the requirements of this specification. Such support shall include, but shall not be limited to, the following:

(a) Maintainability indoctrination of personnel.

(b) Maintainability design review throughout the development and production program to assure that maintainability is being considered as a design goal.

(3.1.1.2) Maintainability design guides. - The contractor and his personnel shall familiarize themselves with Publication NAVSHIPS 94324, and make maximum use of the design guides therein.

(3.1.1.3) Maintainability during design and production. - The maintainability evaluation procedure and maintainability test described in the appendix shall be used for evaluating the maintainability of equipments and systems in the final design stage, and in the preproduction and production stages (see Sections 30 and 40).

(3.1.1.4) Maintainability prediction during preliminary design stage. - In the preliminary design stage (see 6.3.3) the contractor may use any evaluation method and any schedule of evaluation suitable to him to assure himself of compliance with this specification in the final design stage and in the preproduction and production stages. Four evaluation methods for various stages of development and design are presented in the appendix (see Section 50).

(3.2) Maintainability requirements. - The procuring activity will specify an equipment repair time (ERT0 in the detailed equipment or systems specification. (See 6.4) The design of the equipment or system shall be such that the geometric mean of all active repair time intervals required to repair independent failures shall not exceed the specified ERT. Compliance with this requirement will be verified in the final design stage, and in the preproduction and production stages when the following criteria are met.

(6.4) Maintainability specification method. - The value of Equipment Repair Time (ERT) to be specified in the detailed equipment specification (See 3.2) should be determined using the following expression:

$$ERT \text{ (specified)} = 0.37\ ERT_{max}.$$

where (a) ERT_{max} = the maximum value of ERT that should be accepted no more than 10 percent of the time, and (b) 0.37 = a value resulting from application of "Student's t" operating characteristics and that assures a 95 percent probability that an equipment having an acceptable ERT will not be rejected as a result of the first maintainability test when the same size is 20, and assuming a population standard deviation (σ) of 0.55.

(3.2.1) Maintainability requirements in final design stage. - The contractor will be considered to have met the specified maintainability requirements in the final design stage and prior to fabrication of the preproduction model (see 6.3.5), when the calculated geometric mean-time-to-repair, determined by the maintainability evaluation of the final design is not more than the specified ERT (see 4.3).

(4.3) Maintainability evaluation of final design. - Maintainability evaluation of the final design shall be performed before starting fabrication of the preproduction model (see 6.3.4). The final determination of the schedule for performing the maintainability evaluation of the final design will be made by the procuring activity.

(3.2.2) Maintainability requirements in the preproduction stage. - The contractor will be considered to have met the maintainability requirements for the preproduction model when the measured geometric mean-time-to-repair ($MTTR_G$) and standard deviation (S), as determined in accordance with (4.4) produce the following result:

$$\log MTTR_G \leq \log ERT + 0.397\ (S)$$

where (a) log ERT = the logarithm of the Equipment Repair Time specified in 3.2, (b) log $MTTR_G$ = the value determined in accordance with 40.5.1, and (c) S = the value determined in accordance with 40.5.2.

(4.4) Preproduction maintainability test. - The preproduction maintainability test shall be performed on the preproduction model (see 6.3.5) and before the start of production.

(3.2.3) Maintainability requirement during production. - The contractor will be considered to have met the maintainability requirements for production models if no design changes or modifications are introduced following acceptance of the preproduction model or if maintainability of the equipment or system has not been degraded below the specified ERT (see 3.2) by the introduction of design changes or modifications. (See 4.5).

(4.5) Maintainability design review during production. - Whenever design change(s) are proposed for any reason during production and when so directed by the procuring activity, the contractor shall review the proposed change(s) to assure that the overall maintainability of the equipment will not be degraded as a result of the change(s). This review shall include a description of the proposed change(s) and a revision of the maintainability evaluation of final design of (4.3) reflecting the overall effect of the change(s). If, in the opinion of the procuring activity, there is a possibility that degradation of the overall maintainability will occur as a result of the design change(s), the procuring activity reserves the right to require a maintainability test to be performed on a production model incorporating the design change(s) to determine the extent of such degradation. The particular model to be tested will be selected by the procuring activity. When such test is required by the procuring activity, the test shall be performed by the contractor and in accordance with section (40) of the appendix. Acceptance criteria for this test shall be the same as for the preproduction maintainability test (see 3.2.2), with the noncompliance provisions of (4.4.2) applicable. When the test demonstrates that the equipment maintainability does not meet specified maintainability requirements, production shall be suspended pending coordination between the contractor and procuring activity to resolve problem areas in the design.

(3.3.1) Anticipated nonconformance. - In the event the contractor's maintainability evaluations during the preliminary design stage indicate that the specified maintainability will not be obtained within the existing state-of-the-art, the contractor shall submit a report to the procuring activity explaining:

(a) The reasons why the specified maintainability cannot be obtained,

(b) The specific level of maintainability that can be achieved; and,

(c) The design changes necessary for achieving this level of maintainability.

(3.3.2) Nonconformance of final design. - In the event the calculated geometric mean-time-to-repair of the final design does not meet the requirement of 3.2.1, the contractor shall prepare and submit to the procuring activity for approval, a proposed program for accomplishing such design changes as are required to insure that the maintainability requirement of the final design will be met. Implementation of the proposed design changes approved by the procuring activity will be in accordance with the terms and conditions of the contract.

(3.3.3) Noncomformance of preproduction model. - In the event the equipment or systems fail to meet the requirements of 3.2.2 after the second maintainability test (see 4.4.2), the contractor shall effect such modifications as are considered necessary by the procuring activity to assure compliance. Following such modifications, the test of 4.4 shall be repeated.

(3.3.4) Nonconformance of production model. - In the event the equipment or system fails to meet the requirements of 3.2.3 the contractor shall suspend production pending coordination with the procuring activity to resolve problem areas in the design.

(3.4) Reports. - The contractor shall submit maintainability evaluation and test reports to the procuring activity as follows: (3.4.1) Final design maintainability evaluation report, (3.4.2) Preproduction maintainability test report, and (3.4.3) Production maintainability review reports.

(3.6) Maintainability test technician. - Unless otherwise specified in the contract, or by the Contracting Officer after award of the contract, the procuring activity will provide an Electronic Technician who will perform the test repair actions of the maintainability test described in Section 40 of the appendix. When, in the interest of the procuring activity, the contractor is required to furnish a technician for performances of the test repair actions, the contractor will be so notified not later than 30 days prior to the date schedule for the start of the test.

(4.1) Responsibility for inspection. - Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any commercial laboratory acceptable to the Government. The Government reserves the right to perform any of the inspections set forth in the specification, where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

(4.2) Classification of inspection. - Maintainability inspection shall be classified as follows: (a) maintainability evaluation of final design (see 4.3), (b) preproduction maintainability test (see 4.4), and (c) maintainability design review during production (see 4.5).

(6.5.2) Maintainability Specification Criterion. - The criterion ($ERT = 0.37\ ERT_{max}$) given in 6.4 establishes an equipment repair time value to be specified as the maintainability requirement by the writer of the detailed equipment or system specification. It is based on establishing a maximum acceptable (upper limit) value of ERT_{max} from known operational or availability requirements, and determining from this, an AQL of specified ERT. This specified value of ERT established by the criterion of 6.4 is such that if the maintainability test resulted in a measured $MTTR_G$ at exactly the acceptance limit (that is, $\log MTTR_G = \log ERT + 0.397 (S)$) the second time the test of 20 repair time measurements was performed, and after failing the first test, there will be a 90 percent probability that the equipments or system has a true $MTTR_G$ less than ERT_{max}.

(5.5.2.3) Therefore, the specification writer should first establish the ERT_{max} (based on known operational requirements, and so forth) which cannot be accepted more than 10 percent of the time. The specified value of ERT to be included in the detailed equipment or system specification is determined from ERT_{max} using expression in paragraph 6.4.

3.3.2 WR-30, Integrated Maintenance Management for Aeronautical Weapons. Weapon Systems and Related Equipment, Bureau of Naval Weapons.

(1.1) This document establishes the policy, terms and conditions governing the implementation and execution of an integrated maintainability and support program for weapons, weapon systems and related equipments to be procured under the contract in which this document is cited. It is the specific intent of this document to charter the Integrated Maintenance Management Team to manage the total Logistic Support Program. Accordingly, this document is designed to develop, early in a program, a maintenance plan which is tailored to specific commodities and contracts.

(3.1.1) Organization. - In order to satisfy the overall objective of the requirements contained herein, it is essential that the Government and the contractor each establish an organization to achieve the integration and management of maintenance resources. In recognition of this requirement, the contractor shall establish an appropriate organization with expressed authority and responsibility for responding to such requirements.

(3.1.2) Management Team Establishment and Composition. Within thirty days subsequent to award of contract wherein this document is cited, the Government will establish an Integrated Maintenance Management Team. The composition of the Management Team will include the contractor and Government personnel responsible for specific elements of this document.

(3.1.3) Planning Conference. - At a date mutually acceptable to both the Government and the contractor, but in any event not later than 60 days subsequent to the establishment of the Integrated Maintenance Management Team, the Government will convene the Team for a planning conference for the purpose of reviewing, modifying, and approving the contractor's detailed plans for satisfying the requirements of this document.

(3.1.6) Integrated Maintenance Management Plan. - The contractor's documented Integrated Maintenance Management Plan shall be presented for approval at the planning conference. The plan shall contain the following as a minimum: (a) Management Program Section, (b) Maintainability Program Section, (c) Personnel and Training Program Section, (d) Publication Program Section, (e) Augmented Support Program Section, (f) Government Support Program Section, and (g) Facility Requirements Program Section.

(3.1.7) Maintenance Engineering Analysis Record (MEAR). - The MEAR shall be utilized for management and control of the maintainability program and the integration of maintenance resources. The contractor shall prepare MEAR's in accordance with Appendix A during the development program and complete them on a continuing basis in accordance with the schedule agreed upon during the planning conference. MEAR's shall be prepared for the end article; functional systems, assemblies; equipment type items which are programmed for independent overhaul, repair or parts replacement; designated special support equipment; and other items to such range and depth as considered necessary to insure adequate maintenance resource support.

(3.1.9) Contractor Maintenance and Failure Data Collection. - The contractor shall establish and implement a data collection system which will be compatible with the data collection program in effect by the using activity. The contractor will commence data collection at that point in time when hardware is in existence and continued throughout the Augmented Support Program.

(3.2.2.4) Quality of Design. - During the design phase, the following maintainability objectives and related technical, economic and operational constraints shall be considered as a minimum to determine the optimum manner of satisfying the maintainability requirements for the end articles.

(a) Design so that the mean time to accomplish scheduled and unscheduled maintenance is within the target objectives which must be met to satisfy the operational plan for use.

(b) Design to minimize the complexity of frequently performed maintenance tasks (for example: servicing, calibration, adjustments, time-phased replacements, scheduled inspections, etc.).

(c) Maximize the extent to which equipment and system performance can be verified, and system calibration performed on the end article with minimum need for support equipment.

(d) Design for rapid and positive recognition and isolation of equipment malfunction or marginal performance.

(e) Design to require the minimum personnel skills and training needed to develop adequate maintenance proficiency.

(f) Design to require minimum numbers and types of facilities, support equipment (special, general and standard) required to perform maintenance.

(g) Design to require the minimum number of parts, replacement spares, and consumable maintenance materials, by use of military standard items, standard commer ial items, multiple use of the same components in the system, maximum use of components used in previous systems and maintenance of a high level of interchangeability within the system, and between various series or models of the same system.

(h) Design to enhance and facilita e maximum field and organizational self-sufficiency, within the t chnical, economic, and operational framework contained in the Integrated Maintenance Management Plan.

(i) Design for the optimum accessibility in all systems, equipment and components requiring maintenance, servicing, inspections, removal or replacement.

(j) Design equipment and components which are subject to maintenance to eliminate the possibility of improper installation.

(k) Design for maximum safety for both personnel and equipment involved in the performance of maintenance.

(l) Wherever possible and logistically practical, use self-adjusting, self-calibrating and self-checking equipment.

(m) When sealed or encapsulated components are used which are subject to maintenance, repair or modification, they shall be designed, when practicable, to facilitate unsealing and resealing by maintenance personnel.

(3.2.2.6) Design Reviews: Design reviews for maintainability requirements shall be accomplished prior to release of system installation drawings and assembly production drawings. These reviews shall be directed toward an analysis of troubleshooting techniques, accessibility, compatibility, and adequacy of support equipment, human engineering, and life support considerations, training requirements, and maintenance support costs. For items covered by MEAR's the contractor shall not release drawings for initial fabrication or release purchase orders for procurement until the maintenance requirements and tasks have been identified and analyzed. Certification that such review has been made shall be indicated by appropriate drawing title block signature and date.

(3.2.4) Maintainability Design Trade-offs. To achieve optimum operational capability, design trade-offs may be necessary. Maintainability evaluations shall be made, as appropriate, on a continuing basis, as a part of system engineering studies to establish support consequences of design approaches in terms of maintenance resource requirements and development costs. Factors to be considered in determining possible trade-offs are as follows: Criticality of failure, equipment reliability, economic constraints, and performance requirements.

(3.3.3) Personnel Training Requirements. The contractor shall provide a summary of training requirements in accordance with WR-25 to insure that military personnel will be capable of maintaining the end article and related support equipment. The training requirements shall be directly related to the maintenance requirements contained in the MEAR's and shall emphasize new materials, training devices and techniques not currently in use or which are not readily adaptable to existing military training programs.

(3.4.1) Publication Integration. The contractor shall insure that data generated as the result of the maintenance engineering analysis is appropriately used to provide the basis for publications and manuals required by publication specifications cited separately. It is essential that the content of technical manuals, which are considered a maintenance resource, reflect the proper inter-relationship of scheduled and unschedule maintenance requirements, tasks, support equipment and material requirements and maintenance level capability.

(3.5.2.1) Contractor Acquired Spares and Repair Parts Support Material List; Preparation of. The contractor shall prepare, on the basis of MEAR's, support material list(s) for spares and repair parts in accordance with Appendix B. These lists shall include contractor and vendor items acquired to support the end article for the duration of the Augmented Support Program.

(3.5.4.1) Special Support Equipment Design. The contractor shall immediately investigate requirements for SSE as substantiated by maintenance engineering analysis. Concurrent with maintenance engineering analysis, the contractor shall proceed with design or engineering study and shall prepare maintenance engineering analysis on end items of support equipment as determined necessary.

These procedures are applicable to contractor designed and fabricated SSE as well as SSE designed and/or fabricated by vendors or subcontractors. The equipment concerned is considered to be of the type necessary for service, maintenance, test, repair or overhaul of the end article and systems or components thereof and not the type required for developmental qualification or highly specialized technical laboratory type equipment. The Integrated Maintenance Management Team shall supply supplemental maintenance policy on any item of support equipment requested by the contractor. Unless otherwise specified, design requirements for special support equipment shall be in accordance with the specifications listed in paragraph 2.1 of this document, except that special support equipment required solely for overhaul or depot use may be designed in accordance with best commercial practices.

(3.7.1) Control Stages: A maximum of five stages for verification of maintainability and integration of maintenance resources are required for control purposes. These stages are as follows:

(3.7.1.1) Stage One. At the planning conference, the contractor shall present data submitted during the proposal, updated as appropriate.

(3.7.1.2) Stage Two. Stage two shall be progressively implemented during breadboarding or mock up of the contract end article, its systems and equipment, including special support equipment. During this stage, the contractor shall evaluate accessibility, simplicity, equipment size, working environment, maintenance resource requirements and human engineering considerations. The initial maintainability predictions and maintenance resources requirements shall be verified and updated during this stage.

(3.7.1.3) Stage Three. Stage three shall be conducted on the first representative production end article which has been identified by the contractor and scheduled specifically for this purpose. During this stage the maintainability program requirements shall be evaluated to insure that the operational requirements can be met without exceeding programmed maintenance resources. In addition, this stage shall include evaluation of compatibility between maintenance resources. Information feedback will be initiated from observed maintenance action so that early corrective action can be taken or initiated.

(3.7.1.4) Stage Four. Stage four will occur during trials at which time the achievement of the end article maintainability requirements will be demonstrated. The demonstration shall be performed on maintainability test aircraft as specified in the test program. The specific time phasing of demonstrations and proposed requirements to be demonstrated shall be stipulated by the contractor and shall be made a part of the maintainability program plan.

(3.7.1.5) Stage Five. Verification of the in-service and article maintainability characteristics will be accomplished by the Government in-service verification will be accomplished using only these tools, equipment, data, training, personnel, and material resources which have been programmed and provided as a result of the application of this document.

3.3.3 MIL M 26512C(USAF) Maintainability Requirements for Aerospace Systems and Equipment, U. S. Air Force.

(1.1) This specification establishes the general Maintainability requirements for systems and equipment and provides maintainability program policy and procedures.

(3.1) General Maintainability Requirements. - The system/equipment maintainability characteristics shall be such that the maintenance required to meet the planned mission can be accomplished within the limits specified in the system/equipment specification or work statement. The maintenance requirements specified shall apply to all levels of maintenance in the planned maintenance environment, and, depending upon the mission of the system/equipment, shall be stated in quantitative terms such as:

(a) Time (e.g. mean and maximum down time, reaction time, turn around time, mean and maximum times to repair, etc.)

(b) Rate (e.g. maintenance manhours/flying hour, maintenance manhours/specific maintenance action, operational ready rate, maintenance hours/operating hours, etc.)

(c) Maintenance complexity (e.g. number people and skill levels, variety of AGE, etc.)

(d) Maintenance costs (e.g., maintenance costs per year, etc.)

(e) Accuracy (e.g., tolerances of performances).

(3.2) Maintainability Design Principles. - The design of all equipment comprising the system for which the contractor has responsibility shall be so developed that an optimum mix of personnel skills and training, equipment complexity, performance, and reliability will be attained through application of maintainability principles.

(a) Design to minimize the complexity of maintenance tasks.

(b) Design for rapid and positive recognition of equipment malfunction or marginal performance.

(c) Design for rapid and positive identification of the replacement defective part, assembly, or component.

(d) Design to require the minimum maintenance skills and training needed to develop adequate maintenance proficiency.

(e) Design to require minimum numbers and types of tools and test equipment (special and standard) needed to perform maintenance.

(f) Design for the optimum accessibility.

(g) Design for maximum safety for both equipment and personnel involved in the performance of maintenance.

(h) Maximize the extent that performance can be verified, malfunctions anticipated and located, and calibration performed.

(i) Design so the mean time to accomplish schedule and unscheduled maintenance is sufficiently low so as to assure the attainment of specified availability of the system/equipment.

(j) Design to enhance and facilitate all levels of maintenance action.

(3.4) Maintainability Characteristics. - The maintainability characteristics of the equipment and components of the system shall be determined or predicted in terms of their contribution to the overall system maintainability characteristics required to achieve the specified system requirements at each level of maintenance. Factors considered shall include but not be limited to mean-time-between-failures, mean time for repair, mean time for scheduled maintenance, operational requirements, skills, special equipment, levels and location of facilities, and mean downtime.

(3.5.3.2) Specific maintainability program elements. - The following are the minimum program elements which shall be incorporated into the contractor's maintainability program.

(a) Design assistance. - Concurrent with the development of the proposed program plan, the contractor's maintainability organization shall begin to provide design engineering with maintainability design guidelines and techniques for achieving the maintainability requirement.

(b) Design reviews. - Provisions shall be made to assure the the accomplishment of design reviews at the most appropriate stages of system/equipment acquisition.

(c) Review of design changes. - Provision shall be made to assure review of all proposed design changes for maintainability quantitative and qualitative effects.

(d) Corrective action system operation. - The maintainability organization shall assure that problems affecting the maintainability of system/equipment shall be corrective action responsibility assigned and shall follow-up for timely resolution of such problems.

(e) Maintainability predictions. - Provision shall be made for prediction of system/equipment maintainability at selected control points during system/equipment acquisition.

(f) Test and demonstration. - While preliminary testing and demonstration may, where feasible, be performed concurrently with breadboard, environmental, or other tests required by the design and development program, provisions shall be made for formal maintainability tests on delivered article(s).

(g) Maintainability indoctrination or training as appropriate of contractor personnel. - Provisions shall be made for appropriate maintainability indoctrination of contractor personnel, such as, design engineering and manufacturing quality control in the requirements and objectives of the maintainability program. This indoctrination may take the form of lectures, training films, workships, etc.

(h) Logistic support model. - Provisions shall be made for the Contractor's maintainability organization to participate in the development of the logistic support model.

(i) Maintainability analysis. - Identification and management of the maintainability design and all prerequisite resources shall be accomplished through the use of analysis techniques. A maintainability engineering analysis of the system shall be accomplished concurrently with the design effort to provide a systematic definition of the maintenance tasks that will be required in support of the system/equipment and AGE.

(3.6) Maintainability Design Trade-offs. - To achieve optimum operational capability, design trade-offs may be necessary. The major areas involved are impact of equipment malfunction, reliability of equipment, economic limitations, and performance requirements.

(4.2) Maintainability Demonstration. - Maintainability shall be quantitatively demonstrated and evaluated. One method for accomplishment will be found in Appendix A. The contractor may propose alternate techniques.

(4.3) Maintainability Records. - The contractor shall establish and maintain records of maintainability information pertaining to the contract. These records shall be available for inspection by the applicable procuring activity throughout the contract.

3.3.4 MIL-S-23603(WEP) System Readiness/Maintainability, Avionic Systems Design, General Specification for:

(1.1) Scope. - This document specifies one of the major requirements for System Effectiveness as it relates to Avionic systems and subsystems (See 6.1.9). Equipment complying with these requirements shall be designed to meet the requirements for maintainability and system readiness without reduction in the functional system performance. All levels of maintenance including certain airborne maintenance functions are considered in this specification. (The maintainability terminology appearing in this specification is defined in Par. 6.1. The interrelationship of the terms is shown in Chart I).

(3.3.1) Operational Maintainability Requirements. - The qualitative and quantitative characteristics of the equipment indicated in 1.2 shall be such that it will be possible in 95% of all the cases of failure, to perform all corrective organizational maintenance actions, other than combat damage, resulting from two hours of combat flight operations within a turn around period (Max. 4.2.1 (3)) not exceeding 3 minutes. As here applied an organizational corrective maintenance action includes the following: (See 6.1 for definitions of terminology).

(1) Recognition of a fault.

(2) Isolation of the fault to a Weapon Replaceable Assembly (WRA) or to a Maintenance Module Mother Board (See 6.1).

(3) Repair of the fault.

(4) Check out of the repair.

(3.3.2) Maintainability Indices for Organization Maintenance. -

(3.3.2.1) Light Replaceable Assembly (LRA) Ratio - The ratio of the number of Light Replaceable Assemblies (LRA's) to the total number of Weapon Replaceable Assemblies (WRA's) (which is equal to the sum of the Hard Replaceable Assemblies (HRA's) plus the LRA's) shall not be less than 0.90 unless otherwise specified in the detail specification. An example showing computation is shown in figures 1 and 1A. (See 6.1)

(3.3.2.2) Non-Ambiguity (N-A) Ratio - The ratio of the number of WRA's fault-isolated directly with built-in test features and without ambiguity to the total number of WRA's shall not be less than 0.95 unless otherwise specified in the detail specification. An example showing computation is shown in figure 1 and 1A.

(3.3.2.3) Fixed Interface (FI) Ratio - The ratio of the number of WRA's which do not require adjustment or trimming at installation in the aircraft to the total number of WRA's shall be optimized and shall not be less than 1.0 unless otherwise specified in the detail specification. An example of computation is shown in figures 1 and 1A.

(3.3.3) Maintainability Indices for Intermediate Maintenance. -

(3.3.3.1) Quick Replaceable Assembly (QRA) Ratio - The ratio of the number of Quick Replaceable Assemblies (QRA) to the total number of Shop Replaceable Assemblies (SRA) (which is equal to the sum of URA's, the Bench Replaceable Assemblies (BRA) and the Inplace Repairable Assemblies (IPRA) shall not be less than 0.9 unless otherwise specified in the detail specification. An example of computation is shown in figures 2 and 2A. For the definition of the terms SRA, URA, BRA and IPRA, see 6.1.

(3.3.3.2) Shop Non-Ambiguity (SN-A) Ratio - The ratio of the number of SRA's directly isolated and without ambiguity to the total number of SRA's shall not be less than 0.9 unless otherwise specified in the detail specification. An example of computation is shown in figures 2 and 2A.

(3.3.3.3) Shop Fixed Interface (SFI) Ratio - The ratio of the number of SRA's which do not require adjustment or trimming at installation in a WRA to the total number of SRA's shall be optimized and shall not be less than 1.0 unless otherwise specified in the detail specification. An example of computation is shown in figures 2 and 2A.

(3.4.2) Test Program Outline - No later than 120 days prior to delivery and at least 45 days prior to the Maintainability Tests the contractor shall submit for review and approval by the Bureau of Naval Weapons a complete test program outline in the form of Part II of MIL-T-18303. The outline shall contain a list describing the tasks (NC's) selected under 4.2.1 to be simulated during the Maintainability Tests. At this time the government may add or substitute certain tasks for demonstration.

(4.1) Integrated Avionic System/Subsystem Readiness/Maintainability Testing - The Integrated Avionic System/Subsystem shall be tested by the contractor to determine compliance with the requirements of this specification. These tests shall be described in the test procedures outline of 3.4.2 as approved by the Bureau of Naval Weapons. The tests shall be coordinated with the test program for the Integrated System when practicable and economical to do so. At any rate, the tests shall be conducted early enough so that the reporting requirements of paragraph 3.4.3 can be met.

(4.2) Maintenance Task Simulation - The contractor shall perform time studies of maintenance task simulation in a manner representative of system characteristics in actual operation. Time to accomplish each maintenance task shall include recognition time, diagnosis time, repair time and checkout time. It should be recognized that active maintenance down time depends upon the time required to recognize, locate, diagnose, repair and check out the repair of an equipment malfunction. Furthermore, the amount of required maintenance depends upon the equipment reliability. Therefore, in order that the simulated maintenance tasks used in the maintainability demonstration will be representative of normal operation all of the above contributors to active maintenance time shall be considered in the task selection unless otherwise specified. Selection of maintenance tasks shall be accomplished in accordance with 4.2.1. For the purpose of maintainability demonstration, supply down time and waiting or administrative down time shall be excluded.

4. SUMMARY

In this chapter we have outlined the need for specifications, the complexity of the specification tree, and the problems incident to this complexity and the reliability and maintainability technology. The three basic kinds of specifications are described.

A selected list of 20 specifications, standards, and references is given, embracing those most commonly used to contract for reliability and maintainability. Detailed abstracts from the major specifications are given, grouping like subjects together for easy reference.

Chapters 22 and 23 contain recommended language selected from these specifications and modified or supplemented wherever improved practices are available. For a large program such language becomes part of the Reliability and Maintainability Program Plan. For small programs the Chapter 22 and 23 language, or any other in this Chapter 17, may be used directly as appropriate.

5. REFERENCES

(1) Reliability of Military Electronic Equipment by the Advisory Group on Reliability of Electronic Equipment (AGREE), Office of the Assistant Secretary of Defense, Department of Defense, 4 June 1957, Superintendent of Documents.

Chapter 18

PARTS ENGINEERING

Chapter 18

PARTS ENGINEERING

Probably no other contractor activity has a greater impact on system or component reliability than his attention to the reliability of the parts he selects and uses. This is true because, in a typical design, failure of any one of most parts causes system failure. These are called "critical" parts, as opposed to other parts whose failure would not cause system failure. Failure of a part is its departure from the functional specifications upon which its application depends, including degradation or cessation of function.

But it does not follow that if all parts have perfect reliability, the system will have perfect reliability. This is so because the application of parts and their interfaces, such as tolerance drift compatibility, can be such that the system will fail to function properly even with perfectly reliable parts. Nor does it follow, as one often hears, that parts improvement is the only way to achieve required reliability. One other way is the use of judicious redundancy, which protects the system from failure of certain parts.

So we see that parts control is an extremely necessary, but not sufficient, task to achieve the required equipment or system reliability.

Many contractors have excellent parts control procedures, but many do not. The basic problem is to prevent the selection of parts about which there is inadequate knowledge, or their use in a way that degrades reliability. It is particularly serious in the electronics or mechanisms areas, where the green young engineer can become sold on an elegant new part in the vendors catalog. It is "just what he needs" but has no history, no pedigree, no MTBF rating.

For the BuShips engineer, this chapter presents a picture of the contractor work commonly called "parts engineering", with attention to activities directly affecting reliability. Since there are many such groups that do not yet control reliability in the manner to be outlined, the Bureau engineer should look for evidence that each of these activities is effectively handled by at least some part of the contractors organization. They can be evaluated as discussed in chapter 23 section 4.2.

1. STANDARDS & PREFERRED PARTS

Many design engineers have resisted standardization, on the ground that it restricts their freedom for exercise of unbridled creativity and "progress" to new things. Now that we are bending the objective from "new things" to "thing that keep working", such resistance amounts to poor engineering.

But unless such standards are kept vigilantly up to date with advancing state of the art, they can discourage initiative for new developments. They must be constantly reviewed to add new standards. In the case of new physical hardware standards, very thorough reliability verification must precede their establishment prior to withdrawal (for new design) of obsolete standards. The American Standards Association (1) has been established for national approval of standards sources and for distribution of many standards. Now let's review those pertinent to our needs.

1.1 STANDARD SIZES & VALUES

Reliability is improved by experience. To the extent any manufacturer can produce larger quantities of fewer sizes, he learns more about each size by feedback from more users, and improves his design.

Many years ago the old Radio Manufacturers Association (now Electronic Industries Association) saw the great economic and reliability advantage of establishing stock values. They chose a set of values in which each successive value is $24\sqrt{10}$ greater than the preceding, for $\pm$ 5% tolerance. Then for $\pm$10% tolerance every other value is standard, and for $\pm$20% every fourth value is standard. This system achieved complete coverage of all values, since adjacent high and low tolerances nearly coincide. In Figure 18-4 these values are shown in the "Choice 1, 2 and 3" columns, and each value can be multiplied or divided by 10 or any multiple of 10.

The advent of film-type (carbon and metal film) with much better control of resistance values prompted the military to extend the system to $\pm$1% values, as shown in the Military Standard MS 90169 "Choice 3 and 4" columns. Nearly all resistor and capacitor manufacturers now furnish all of these standard values.

There are many electrical and electronic circuit applications where $\pm$20% resistance or capacitance values are more than adequate. So in the interest of reliability and economy the design engineer should always specify the "Choice 1" values when they will serve

FILM RESISTOR STANDARD VALUES

Choice				Choice				Choice				Choice			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
EIA		MS-90169		EIA		MS-90169		EIA		MS-90169		EIA		MS-90169	
20%	10%	J 5%	F 1%	20%	10%	J 5%	F 1%	20%	10%	J 5%	F 1%	20%	10%	J 5%	F 1%
1.00	1.00	1.00	1.00		1.78	1.78	1.78	3.16	3.16	3.16	3.16		5.62	5.62	5.62
			1.02				1.83				3.24				5.76
			1.05				1.87				3.32				5.90
			1.07				1.91				3.40				6.40
		1.10	1.10			1.96	1.96			3.48	3.48			6.19	6.19
			1.13				2.00				3.57				6.34
			1.15				2.05				3.65				6.49
			1.18				2.10				3.74				6.65
	1.21	1.21	1.21	2.15	2.15	2.15	2.15		3.83	3.83	3.83	6.81	6.81	6.81	6.81
			1.24				2.21				3.92				6.98
			1.27				2.26				4.02				7.15
			1.30				2.32				4.12				7.32
		1.33	1.33			2.37	2.37			4.22	4.22			7.50	7.50
			1.37				2.43				4.32				7.68
			1.40				2.49				4.42				7.87
			1.43				2.55				4.53				8.06
1.47	1.47	1.47	1.47		2.61	2.61	2.61	4.64	4.64	4.64	4.64		8.25	8.25	8.25
			1.50				2.67				4.75				8.45
			1.54				2.74				4.87				8.66
			1.58				2.80				4.99				8.87
		1.62	1.62			2.87	2.87			5.11	5.11			9.09	9.09
			1.65				2.94				5.23				9.31
			1.69				3.01				5.36				9.53
			1.74				3.0[illegible]				5.49				9.76

the purpose, and if not, use Choice 2, etc.

In many cases the design engineer uses precision (film-type) resistors where the larger drift of composition or other resistors cannot be tolerated. But to take advantage of standard part reliability and economy, he must use these specified values even if the precision (nominal value) is not needed. Many companies order only ±1% film-type resistors, to reduce the problem of calculating circuit performance via tolerance evaluation.

While the above system is well-established for small resistors and capacitors, its advantages apply equally well for all kinds of parts that are used in quantity. Screw sizes and threads, and pipe have used similar systems for a hundred years. As our technology develops new kinds of parts, the design engineer can contribute to reliability by specifying values from such systems.

1.2 PREFERRED PARTS

Here a semantic problem has arisen. Several military and NASA agencies have established "standard" parts lists, such as MIL STD 242E. The criteria for inclusion in such lists varies widely, from mere volume of use to fairly rigid life test qualification. Similarly many contractors have established such "standard parts" lists, also with widely-variant criteria. Thus the term "standard part" does not mean the "best part", or parts, to use among alternatives. So the term "preferred part" has emerged, to connote a much higher degree of selectivity. A fairly high proportion of "standard" parts are not eligible for "preferred part" status with contractors working to specified reliability. Let's review the advantages of the establishment of a truly minimum number of preferred parts:

Manufacturers Cost Reduction: Obviously the more a manufacturer can make of fewer types, the lower his unit production costs will be. Moreover, as competitors are attracted by the volume, multiple sources are assured and competitive process refinements drive the price still lower and keep it down.

Reliability: As higher quantities of fewer types are produced, the manufacturer can generally afford more specialized test facilities, and engineering refinement, spreading their cost over more units. He learns more about the failure modes of each type from his own experience and from his customers, and thus can take more remedial action to raise reliability. Since he tests more of them, his confidence level for a given failure rate is higher, or conversely the failure rate is lower for conventional confidence levels.

Contractors Cost Reduction: Since the part manufacturer can afford better testing, and is usually better able to do it than his customer, standardization generally reduces the contractors own verification or acceptance testing. But the sheer reduction of paperwork for multiple specifications, procurement requisitions, purchase orders, and liaison constitutes substantial cost reduction. Parts lists are simplified. Obviously the contractors parts inventory investment and control cost is greatly reduced.

Ownership Cost: As fewer types of parts are required for maintenance, with higher quantities of each, the logistics cost is reduced. Fewer parts have to be stocked on board, at shipyards, at supply centers, and at the manufacturer's plant. Fewer parts are needed in the "pipe line". Fewer parts permits better handling at lower cost. But also the higher reliability of preferred parts reduces maintenance and therefore logistic costs.

Operational Data: Higher quantities of fewer types permit the acquisition of more complete operational information on each part, for feedback to design engineers. And the data has better precision. The design engineer has a more realistic basis for decision.

Tolerance Limits: Part standardization should particularly cover configuration, such as shape, lead length and material, mounting dimensions, etc. Here the Bureau or the contractor can usually specify limits in such a way as to encompass several suppliers standard products to preserve competition, economy, and availability for delivery. To standardize on one suppliers exact design is sometimes necessary, but rarely desirable. Without competition, or with patent advantage over competition, there is not much incentive for reliability and cost improvement.

With the above advantages in mind, many contractors have established policies and procedures that require the design engineer to (a) select and specify a preferred part, or (b) convince a parts engineering specialist that no existing preferred part will serve the purpose. As repeated demands for a kind of part occur, this procedure serves to initiate the establishment of a new preferred part, and possible removal of a superseded part from the preferred parts list. The Bureau engineer can look for and encourage such contractor procedures.

1.3 PREFERRED COMPONENTS

Components such as regulator valves or amplifier circuits, made up of parts, can be either selected from available supplier products or developed by the design engineer, for wide use across a range of higher-level designs.

The above considerations for parts apply equally well to components, though there are fewer such standards and they are more complex. Many contractors maintain a file of thoroughly-proven circuits, which may be either used directly or modified to avoid the unreliability and cost of complete reinvention. But, sadly, the amount of such reinvention in the U. S. must be staggering, for sheer lack of communication.

2. NON-PREFERRED PARTS

As discussed above, some government agencies have established "standard parts" or "qualified parts" lists of parts qualified to some criteria appropriate at the time. Such agencies then take the position that the contractor must obtain their approval to use each part not on the list, as in MIL E 16400E section 3.4.1. The contractor must give his justification, which is given on grounds of performance capability, reliability, cost, etc. Such negotiation is usually conducted with the agency by the contractors parts engineering specialists, who are most likely to have wide knowledge of available part capabilities.

But in order to achieve required reliability, and whether or not the contractors customer has a standard parts list, the same kind of control must be exercised over non-preferred parts. That is, if the contractor has established a good preferred parts list, on which only parts of known history and reliability appear, there must be a procedure that prevents use of other parts until the pertinent preferred parts are adequately considered. This is normally handled by requiring a parts engineering or reliability specialist approval of drawings prior to design review for final release. Some contractors require such approval of all parts procurement requisitions, which is pretty late and requires the parts engineering people to go back over the drawings and analyses anyway.

3. PART SELECTION AND APPLICATION

Two major causes of unreliability are (a) selection of a part without really knowing its reliability history, and (b) improperly using the part in design, so that its capabilities are exceeded. Preferred Parts lists establish a "bank" of known-reliability parts, but they cannot contain all parts needed for a new design.

3.1 KNOWN RELIABILITY PARTS

The achievement of specified component reliability begins with the selection of parts of known reliability. For most situations the component failure rate is the simple sum of the failure rates of its parts whose failure would cause component failure. This is true whether or not the actual part failure rate values are known.

In general the only sources of dependable information on a specific part are the supplier of the part and the users of the part, if they have kept records of failures vs. stress time. And some suppliers are reluctant to disclose such information for fear they will fare unfavorably relative to competition. Some contractors or subcontractors who use the part may keep good records, and may provide such specific information.

One way to get parts of known reliability is to specify the required quantitative value and the verification requirement to parts suppliers, and ask for quotations. Some will decline to quote, indicating they either do not know how to get the required value, or are unwilling to guarantee their assertions. Others will quote without understanding the problem, then later renege when they realize what is required. But many today do understand, do keep test and operational records, and can be relied upon to show convincingly what value they can achieve. And most of these are willing to guarantee the value.

The commonest quantification of parts reliability is in terms of maximum failure rate, or failures per million hours of stress (or, somewhat confusingly, in % failures/1000 hours). But there can be situations where stress time records are impractical, so that maximum unreliability must be specified as the probability of failure in a given production lot or lots, for specified environment and stress. This is roughly equivalent to a fraction of the overlap area between stress and strength distribution curves.

"Established-Reliability Parts" specifications MIL R 38100 (4) are being developed by DOD under Air Force sponsorship, as an out-growth of the Minuteman high-reliability electronic parts program. These specifications call for very tight design and manufacturing controls, special handling, and a continuous test program to verify the achieved reliability. As a result, a 10-to-1 failure rate reduction was achieved for about a dozen common electronic parts, which can be procured from their manufacturers. The program is expected to be expanded to other electronic and mechanical parts. In the meantime some contractors are using the MIL-R-38100 content as a model to develop their own specification to vendors, and the BuShips engineers can do the same for critical requirements but redundancy of specifications should be discouraged.

Today, however, the quantitative reliability records for most specific parts (as opposed to part classes) do not yet exist. The design engineer must then look for other assurance of "known reliability". For example if he knows that hundreds or even dozens of a certain part have been used (stressed) for years, and he can find no evidence that it has ever failed (except by misuse), he has good intuitive confidence that it has high reliability. On the other hand he must systematically and thoroughly look for such evidence of failure before real confidence can develop. The Bureau should require the contractor to seek such evidence.

3.2 PARTS APPLICATION

Improper use of parts utterly wastes the time and cost of careful known-reliability part selection. The selection and application of parts of course constitutes a large part of the design process. It is the design engineer's job to balance dozens of considerations for each decision.

But most design engineers are not experts on more than a few parts with which their experience is extensive. Almost every new design involves parts with which the design engineer is only barely acquainted. To solve this problem most well-organized contractors have long-established groups of parts engineering specialists, each of whom work only with a few kinds of parts. Over a period of time they know more about the capabilities and limitations of some specific parts than anyone in the contractors' organization. The great bulk of this knowledge is perishable, not on spec sheets, not in handbooks.

However it is imperative that the parts specialists know the reliability of each part, and how such reliability is affected by application. Many well-established Parts Engineering groups do not have this knowledge.

Hardly anything will contribute more to reliability than the detailed review of a proposed design by the cognizant parts specialists. When they are inclined to recommend against use of a specific part in a certain way, or to recommend an alternative part or manner of its use, there should be thorough discussion before the design engineers decision is made. Some contractors have procedures whereby only the top Engineering Manager can override a parts engineer's disapproval of a part application. Knowledge of this causes the design engineer to be very sure of his ground before taking a position. The Bureau engineer should make sure some such control is in effect.

3.3 DERATING

Intuitively every design engineer feels that reliability is improved by using parts rated much higher than the expected stress. That is, he "derates" the parts for his application. It is equivalent to increasing the "safety factor". Unfortunately this practice also increases cost, weight, and volume. If operational experience shows no failures, he never knows how much, if any, unnecessary cost, weight and volume he has incurred. We are all aware of such examples of "overdesign". Nevertheless, judicious derating is a powerful aid to reliability. There are two basic approaches:

3.3.1 Derating Factors: In the absence of good failure rate data, the parts engineering specialists may establish quite arbitrary derating factors for each kind of part. These are based on long experience, trial and error, and judgment. They have been quite successful, and are very widely used, but undoubtedly cause some degree of "overdesign". Examples of these are shown in Figure 18-11, used by a major contractor, and 18-12 from MIL HDBK 217. Policies and procedures are established whereby all design engineers are required to use the indicated minimum deratings.

Manufacturers' catalogs are somewhat confusing regarding resistor power rating since they often give three ratings. The most optimistic rating is the manufacturer's (commercial), while the most pessimistic is the MIL-R-93A. The MIL-R-9444 specification permits more power to be dissipated in a given size resistor than MIL-R-93A permits, yet it contemplates a more severe environment. This means that resistors of the encapsulated variety which meet both of these military specifications are much better than the MIL-R-93A requirements and we needlessly penalize ourselves when we derate to these pessimistic watt values.

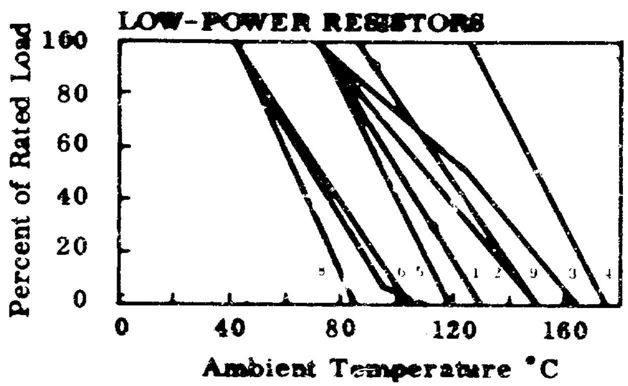
Nearly all transistors are rated by the manufacturer on the basis of an absolute maximum system. These ratings are not conservative

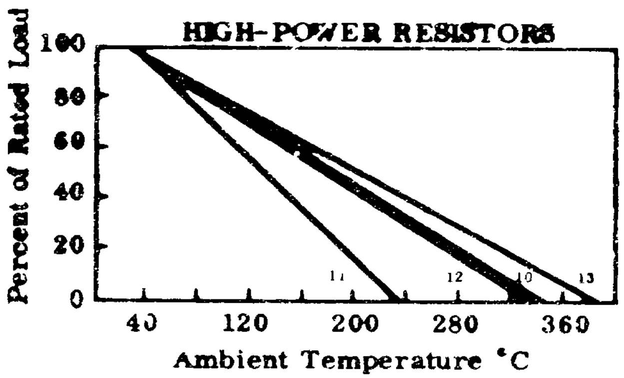
TRANSISTOR DERATING

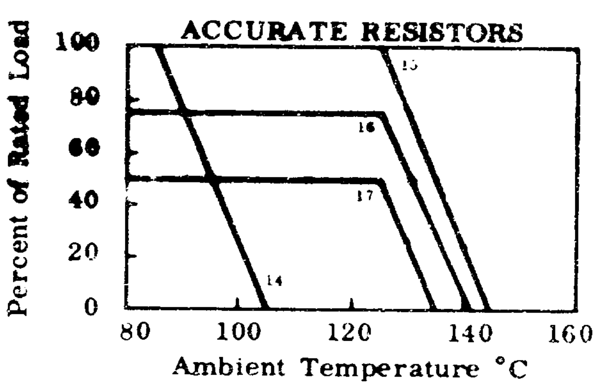
Recommended safety margins

	Broadband IF	DC Regulator	Oscillator	Video Amplifier	Audio Amplifier	Multi-Vibrator	Power + Inverter	Blocking Oscillator
I_{CBO}	2 times maximum specified at maximum voltage and temperature of interest							
V_{CE}	Maximum 3/4 specified maximum BV_{CEO} for peak ac swing		Supply V 1/2 this		Saturation 2 times specification maximum V_{cc} 1/2 of 3/4			Up with temp.
h_{FE}, h_{fe}		1/2 min low-temp	1/2 minimum to 2 times maximum specified			1/2 min, min. temp	1/2 spec. minimum	
$t_{on} + t_{off}$						2 times specified maximum		
f_{hfb}			1/2 min specified			1/5		4/5 min specified
f_{hfe}				2 spec. minimum				
P_c	Junc. max 150°C sil. 85°C germ.		Junc. max 150°C sil. 85°C germ.		3/4 max at max temp.			
BV_{CEO}							Supply V 38%	3 times supply V
Other		R_b 2x max. spec					r_b 2x max. spec	V_{BE} sat. max. + 5V

MIL-HDBK-217 RESISTOR DERATING







Number	Style		Curve
11C	RC		1
10509D	RN	B	2
		D & G	3
		C, E, & F	4
94B	RV	Temp. X, Y	5
19A	RA		6
10683	RF		7
12934B	RR	Class & Grades 1 & 4	8
		2 & 5	5
		3 & 6	9
26C	RW	Temp. V, Y	10
11804C	R		11
22A	RP	< 100 watt	12
		> 100 watt	13
93B	RB	Temp. A	14
		Temp. C	15
944A	AFRT	Tolerance F	15
		D	16
		B, C	17

and, if exceeded, will result in immediate failure or drastically reduced life expectancy of the device. Figure 18-11, previously called out, extracts the derating values from a quite thorough exposition (5) on good transistor circuit design. The following consolidates the best derating practices used by experience design engineers.

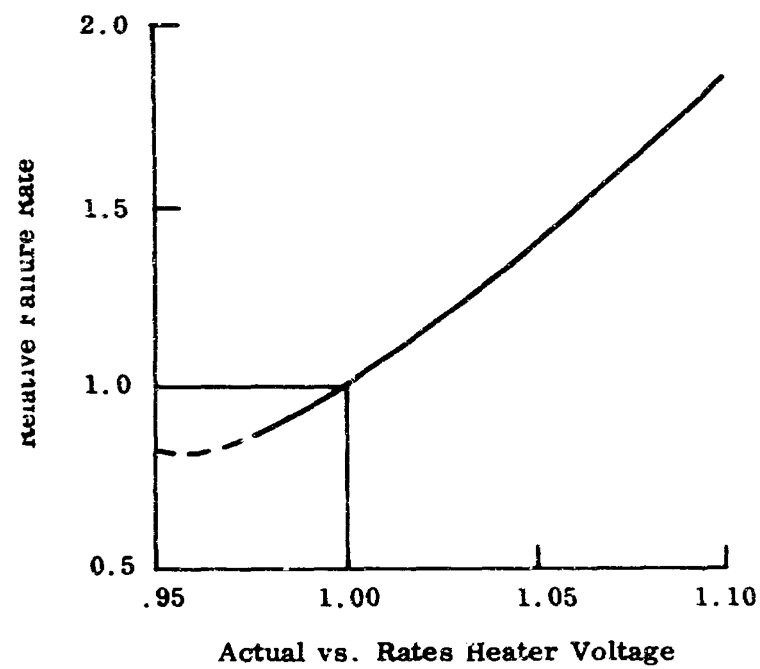
It has been estimated that 95 per cent of all transistor failures are due to voltage breakdown. Although this estimate may be somewhat high, it emphasizes the necessity to derate the voltages applied to transistors to as low a value as possible consistent with required performance. Some research work indicates that the reliability of germanium transistors can be increased by a factor of 10 by operating at half the rated voltage.

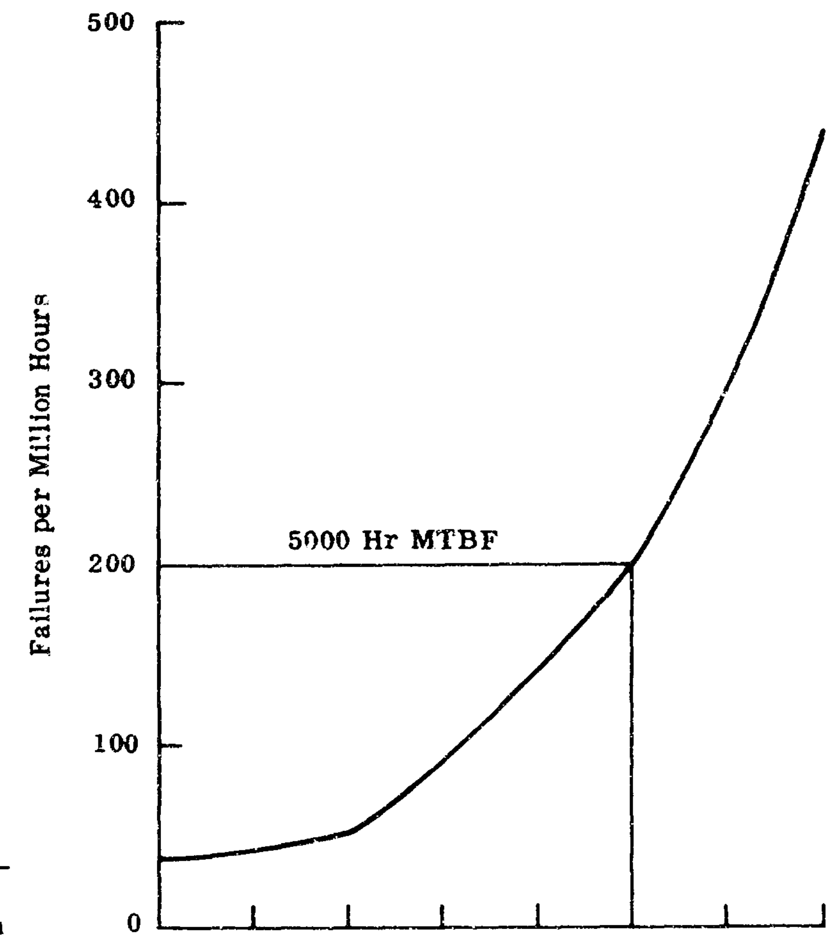
Common practice is to limit the peak collector voltage, including a-c swing and surge voltages, to 75 per cent maximum rated value BV_{CBO} OR BV_{CEO}. Since some types of voltage breakdown occur at lower voltages as the ambient temperature is reduced, the derating factor of 75 per cent should be applied to the breakdown voltage at the lowest temperature of interest. Avalanche breakdown margin should also be checked at the maximum expected temperature.

Junction temperature is an important factor in transistor reliability. Maximum junction temperatures of 150°C for silicon and 85°C for germanium are considered safe. However, reliability is greatly improved if junction temperatures are kept as low as possible. Some researchers indicate the reliability doubles for each 10°C reduction in junction temperature. Normally, junction temperature is determined by the power dissipated in the transistor due to collector current and voltage. However, some applications (e.g. dc to dc converters) will have a substantial amount of power dissipated in the base circuit, this power must be considered when predicting junction temperatures.

3.3.2 Derating vs. Failure Rate: When good failure rate data is available, a more rational approach may be used. The design engineer selects the parts he would like to use, designs the circuit or mechanical assembly, and calculates (usually simple failure rate addition) the total failure rate of his design. If it is too high or borderline, he then refers to failure-rate-vs-stress curves, and derates judiciously until the total is low enough. Examples of such curves are shown in Figures 18-14 through 18-15 - 18-19 from MIL-Hdbk-217. These are "generic" curves, however, useful only for relative failure rate comparison. They do not express absolute values for the specific part selected.

ELECTRON TUBE DERATING





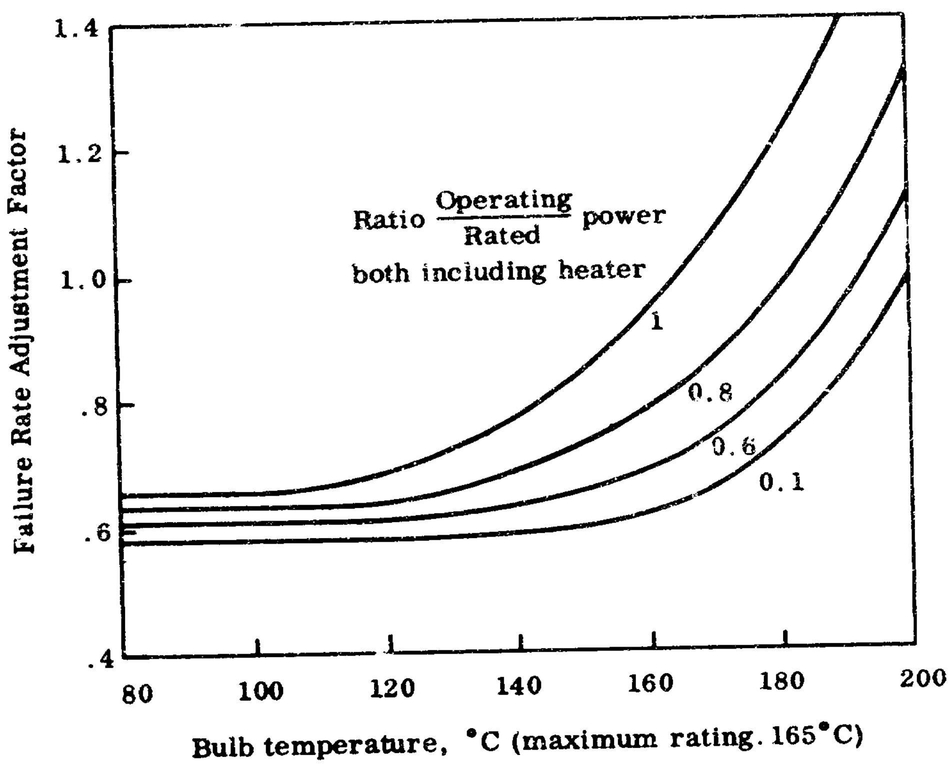
Derating vs. Design Center Values

Use Mil-E-1B maximum ratings available

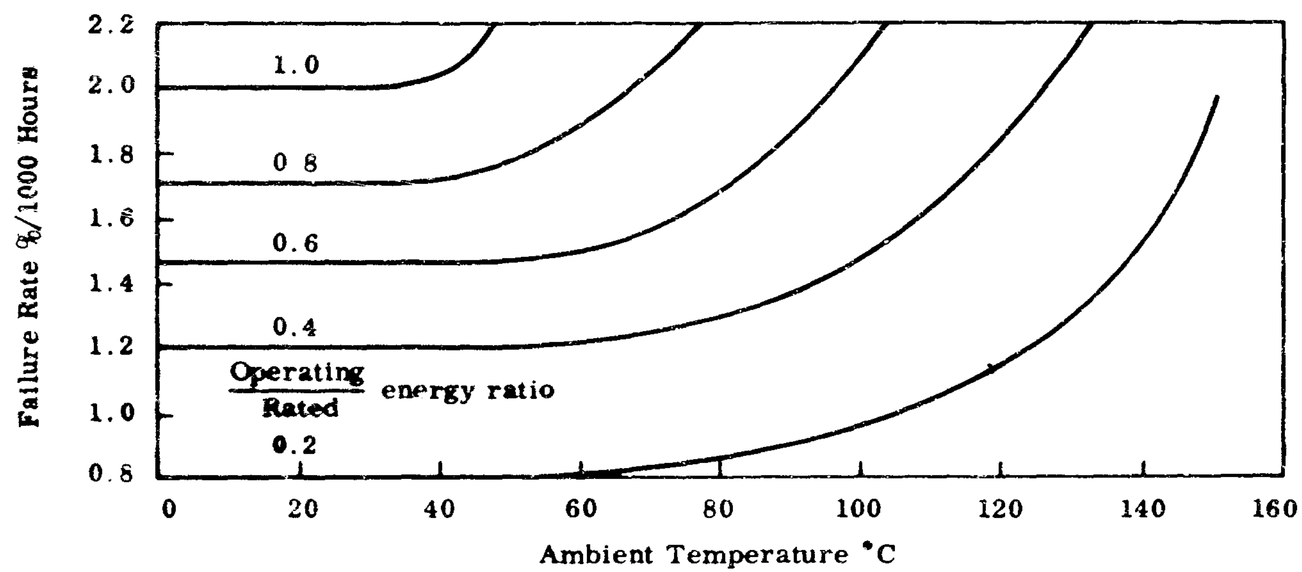
Design center values are normally 90% of maximum

Voltage & Current (except heater) =	50	75	90	90	90	100	110	110
Power (all elements) =	25	50	75	90	100	100	100	125

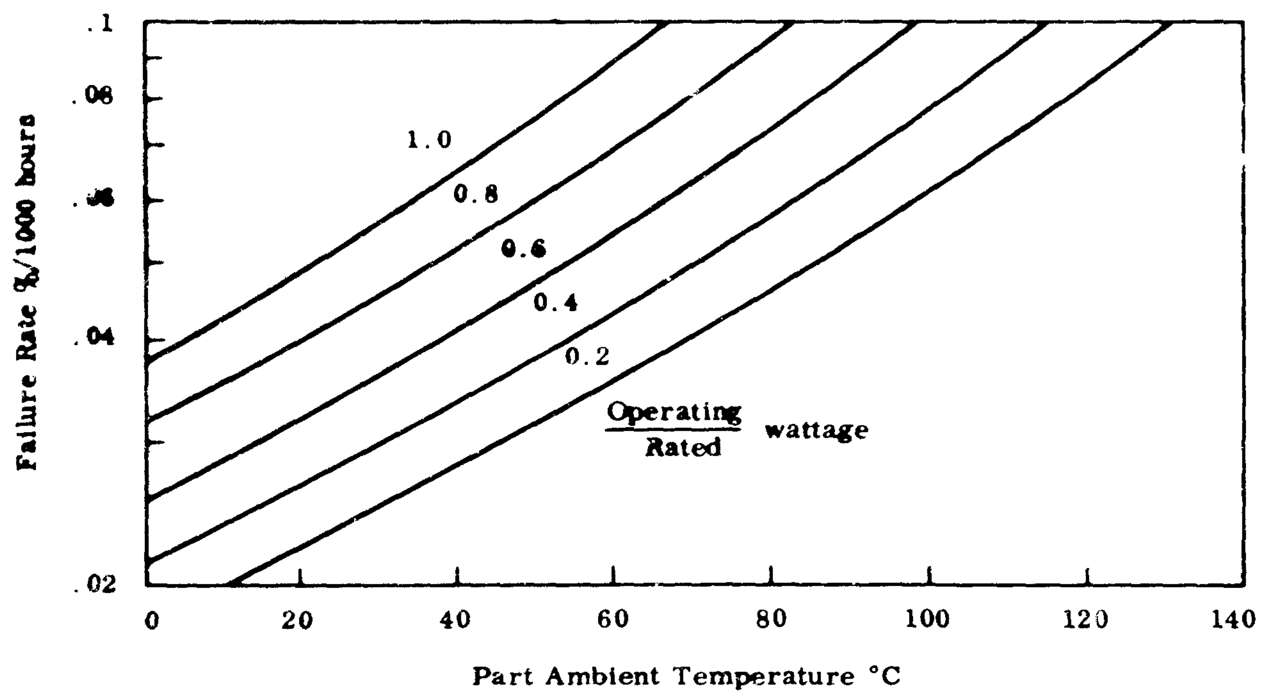
MINIATURE TUBE FAILURE RATE



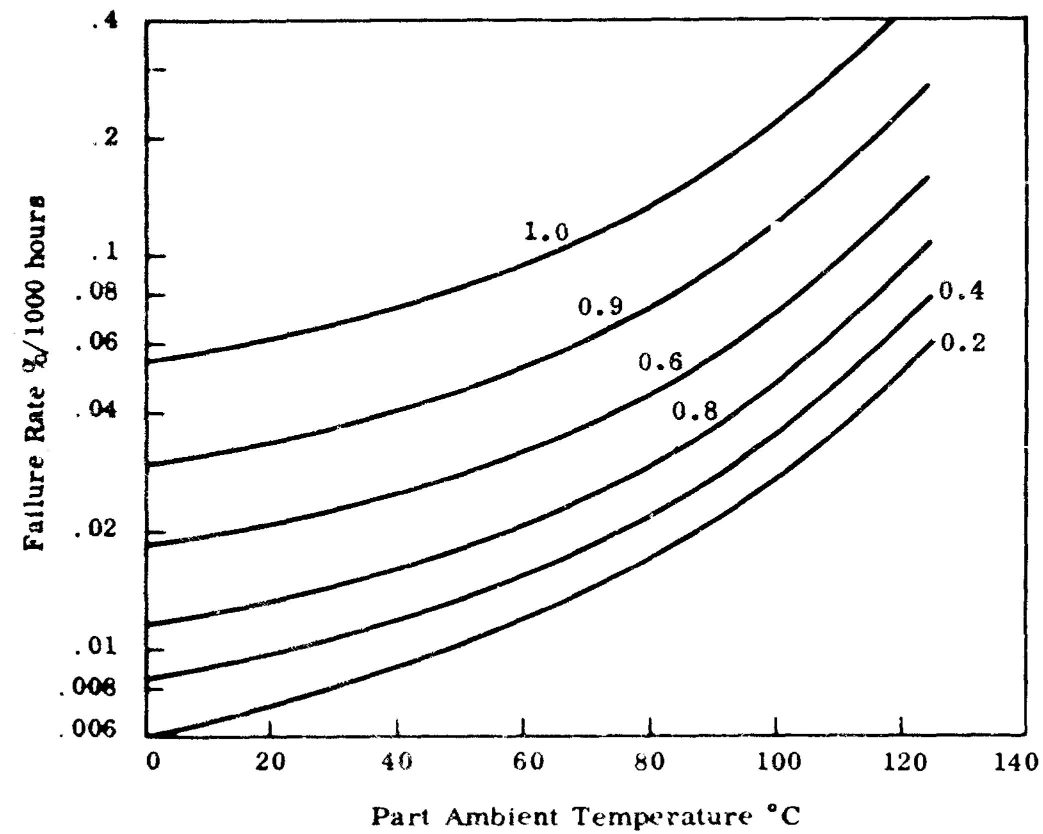
MICROWAVE DIODE FAILURE RATE



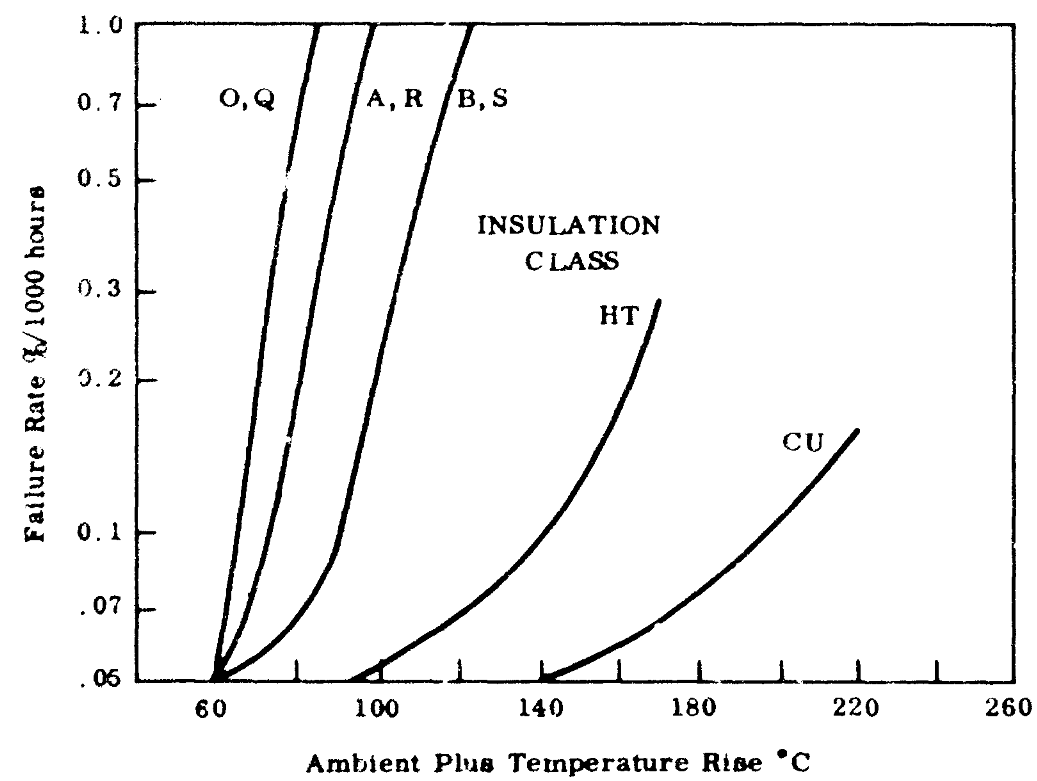
FILM RESISTOR FAILURE RATE



TANTALUM CAPACITOR FAILURE RATE



TRANSFORMER FAILURE RATE



Parts engineering specialists are responsible for keeping up-to-date such data in the hands of the design engineers, particularly as data is collected from actual test and operational experience with the specific parts, and for approving part application on the basis of such derating.

3.3.3 General: In the electronics industry, data (2, 3) on failure rates vs. stress is available for a number of common parts. The curves can be used to get at least a rough idea of the reliability improvement available through derating by any amount.

In the mechanical and structural fields such data is sometimes obtainable from the manufacturer or users, but time rate data is not available yet in handbook form. In using the manufacturer's rating and single design stress values, the design engineer has to keep in mind that they are really distributions, not single values. He has to find out either the worst-case "tolerances" for both stress and strength, or preferably plot the distributions themselves.

The Bureau engineer should make very sure that some such rational derating approach is established and enforced, preferably by cognizant parts engineering specialists.

3.4 TOLERANCE DATA

In quantity manufacture, all parts characteristics have statistical distributions. That is, any one characteristic (such as length or resistance) has a nominal or mean value, and a variance above and below it. We call the extreme values of the variance "Tolerances". These distributions are basically affected by manufacturing lot, and by techniques for selection of close-tolerance parts out of wide-tolerance lots.

In addition to such manufacturing variance there is application variance regardless of quantity. That is, there are distributions of each characteristic resulting from environment (temperature, etc.) stress (pressure, voltage, etc.), and time (cold flow, drift, aging, etc.). Such distributions or tolerances must be added to the manufacturing distributions or tolerances in order to determine the real operational distribution. An example is steam line design where O-rings are used to absorb tolerances.

A design is never complete until the design engineer has made sure that the distributions or tolerances cannot combine in such a way as to interfere with the intended function. The Bureau engineer must make sure that adequate such analysis is conducted.

In a complex circuit, mechanism, or structure it is necessary to consider the overall effect of the expected range of manufacturing variance, operational environment and all stresses, and the effect of time. Chapter 13, section 2.5 outlines Worst-Case Tolerance Analysis, Statistical Tolerance Analysis, and Marginal Checking, all used for this purpose. All such tolerance evaluation depends on some depth of part tolerance data, and the parts engineering specialist again is in the best position to develop, publish, and update such data for broad use for by design engineers. Figures 18-22 through 18-26 show some excellent data (5) for this purpose, not available in the MIL handbooks.

4. PARTS OPERATIONAL DATA

4.1 DESIGN DATA

In order to design to meet a specified reliability, the design engineer must obtain some idea of the reliability of the parts he tentatively proposes to use. Such information is often meager indeed. While some electronic parts data is prolific, it is also contradictory and therefore generates little confidence.

So-called "generic" failure rate data was developed initially by RCA for electronic parts, and subsequently refined by several contractors and government agencies. It is currently available in MIL-Hdbk-217 (2) and the Farada (3) books, and in NAVSHIPS 93820. But this data is subject to wide variance, and useful only for preliminary or comparative analysis. It tells little about the failure rate of a specific suppliers part that the design engineer may consider using.

Very few contractors have developed continuously-operating data-reduction systems that provide information to design engineers in convenient form. Figure 18-27 shows a rather comprehensive system now under development by a major contractor. A "Data Integration" group sets up an automatic "all source" flow of pertinent data from industry (217, Farada, Etc., above), suppliers, design evaluation tests, manufacturing tests, contractor and possibly BuShips tests and Navy operations. Using controlled formats, the group screens the data to weed out the non-significant, interrogates sources where feasible for clarification, conducts running analyses for current estimates, and reduces the result to an updated punch card. The updated cards accumulate,

RESISTANCE VALUE % CHANGES

Effect from initial 25°C value		Allen-Bradley* Composition				Deposited Carbon < 500K		Metal Film** (50 PPM/°C) < 500K	
		< 10K		10K to 1 Meg					
Manufacturing Tolerance, (Typ.)		0	±5	0	±5	0	±1	0	±1
Change at +125°C (Due to temp. coeff.)	No Load	+4	±3	+5	±4.5	-3	±1	+0.15	±0.35
	At 50% Derating	+5.5	±3.5	+6.5	±5	-3.5	±1.4	+0.20	±0.40
Change at +85°C (Due to temp. coeff.)	No Load	+1	±2	+1	±3	-1.7	±0.7	+0.05	±0.15
	At 50% Derating	+2.5	±3.5	+3	±4	-2.5	±1	+0.10	±0.20
Change at -55°C (Due to temp. coeff.)	No Load	+3.5	±3.5	+6	±3	+2.2	±0.9	-0.10	±0.25
	At 50% Derating	+2.5	±2	+4	±2	+1.4	±0.6	-0.07	±0.15
Aging Change, Permanent (With 50% Derating at 65°C, After 100 to 1000 Hours		-0.3	±1.0	-1.5	±1.5	-0.1	±0.5	0	±0.2
Voltage Effect (Due to voltage coefficient, with 100v dc applied)		-0.5	±0.5	-2.3	±0.6	- - - - - - - -		- - - - - - - -	
Soldering Change, Permanent		+1	±2	+1	±2	0	±0.3	0	±0.1

*Composition resistors may suffer a +10% additional change if exposed to 95% relative humidity at 55°C for 100 Hours.

**This column also applies to wire-wound resistors, except for manufacturing tolerance.

NOTE: Derating is with reference to the "application" rating, or allowable load at given conditions.

CAPACITANCE VALUE % CHANGE

Effect from initial 25°C value	Glass		Mica (Dipped, Char. F)		Ceramic Mil Type CK05, CK06		Tantalum (Foil)		Tantalum (Solid)		Paper	
Manufacturing Tolerance (Typical)	0	±5	0	±2	0	±20	0	±20	0	±20	0	±10
Change at 125°C (Due to Temp. Coeff.)	+1.65	±0.1	+0.5	±0.3	+8	±6	+30	±15	+8	±3	+5	±1
Change at 85°C (Due to Temp. Coeff.)	+0.9	±0.1	+0.3	±0.2	-3	±3	+10	±8	+5	±2	+1.5	±1
Change at -55°C (Due to Temp. Coeff.)	-1.0	±0.1	-0.4	±0.2	-10	±5	-14	±5	-7.5	±2	-5	±1
Aging Change, Permanent (With 50% Derating at 65°C, After 100 to 1000 Hours)	-0.02	±.01	+0.1	±.05	-2	±2	-1	±0.5	-0.1	±0.1	+1	±1

R & C OVERALL VALUE % CHANGES

	Temp -55°C to	Resistors: Deposited Carbon (±1%)	Resistors: Allen-Bradley Composition* (±5%) < 10K	Resistors: Allen-Bradley Composition* (±5%) 10K to 1 Meg	Resistors: Metal Film (±1.0%)	Capacitors: Tantalum Solid (±20%)	Capacitors: Glass (±5%)
Sum of Decreases**	+125°C	-3.6 ±1.82	+0.2 ±5.5	-2.8 ±5.62	-0.10 ±1.05	-7.6 ±20.1	-1.02 ±5
	+85°C	-2.6 ±1.53					
Maximum Expected Decrease	+125°C	-5.42	-5.3	-8.42	-1.15	-27.7	-6.02
	+85°C	-4.13					
Sum of Increases**	+125°C	+2.2 ±1.38	+6.5 ±6.42	+7.5 ±7.35	+0.20 ±1.10	+8 ±20.2	+1.65 ±5
	+85°C		+4.5 ±6.42	+7 ±6.16	+0.10 ±1.04	+5 ±20.1	+0.9 ±5
Maximum Expected Increase	+125°C	+3.58	+12.92	+14.85	+1.30	+28.2	+6.65
	+85°C		+10.92	+13.16	+1.14	+25.1	+5.9

*Not including possible +10% change due to humidity.

**Soldering effects included in all cases.

Metal Film resistors and glass capacitors are inherently stable, the manufacturer's tolerance comprising the bulk of the uncertainty of value. For these parts in particular, the manufacturer's tolerance value, if different from that assumed above, should be used in recalculating applicable limits.

VARIATIONS IN TUBES

	Transconductance		Plate Current		Amplification Factor	
	Low	High	Low	High	Low	High
Manufacturing Tolerance	-10 ±10%	+10 ±10%	-15 ±20%	+15 ±20%	-8 ±7%	+8 ±7%
10% Decrease in Filament Voltage	-5 ±3%		-5 ±3%		Negligible	
10% Increase in Filament Voltage		+5 ±3%		+5 ±3%	Negligible	
After 100 hours Use	-6 ±5%		-10 ±5%			+2 ±3%
First Hour after Energizing	±10%	±10%	±10%	±10%	Negligible	

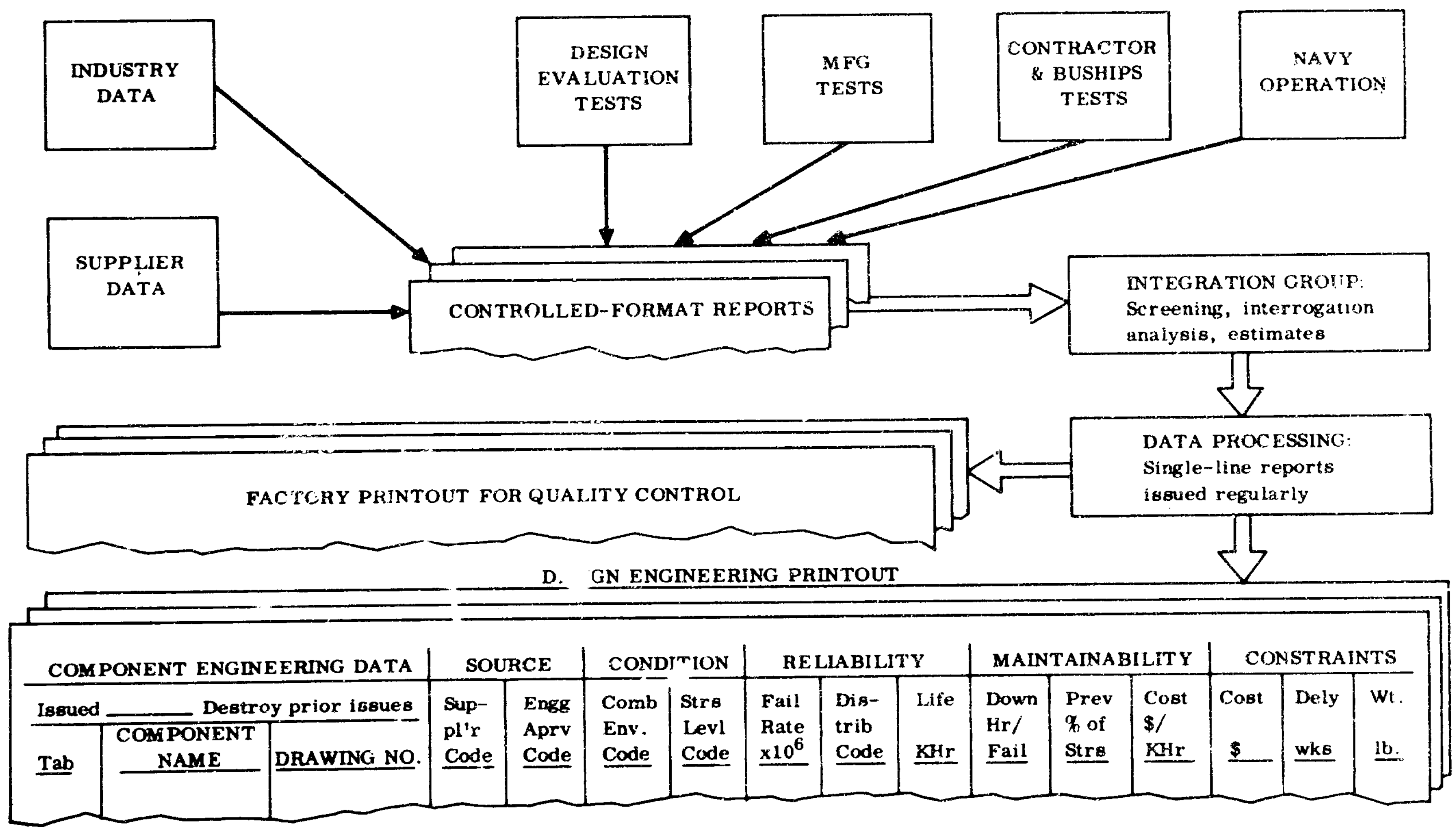
Combining Effects: The effects pertaining to a given situation are combined by addition of the portion of each appropriate change which has a single sign, and by combining each portion which as a ± sign according to the square root of the sum of the squares.

OVERALL VARIATIONS IN TUBES

(operated near their design centers)

	Transconductance		Plate Current		Amplification Factor	
	Lowest Condition	Highest Condition	Lowest Condition	Highest Condition	Lowest Condition	Highest Condition
Including Manufacturing Tolerance	-21 ±15%	+15 ±15%	-30 ±23%	+20 ±23%	-3 ±7%	+10 ±8%
Limits:	-36% to +30%		-53% to +43%		-15% to +18%	
With Manufacturing Tolerance Compensated	-11 ±12%	+5 ±10%	-15 ±12%	+5 ±10%	0	+2 ±3%
Limits:	-23% to +15%		-27% to +15%		-1% to +5%	

INTEGRATED OPERATING DATA SYSTEM



displace prior cards in sorting, and regular monthly printouts are produced.

The design engineering printout across the bottom of the figure (a) identifies each part or component for which data is available, shows (b) the environment (such as ground air-conditioned environment, GAC) and stress (such as 15 kpsi) for which the data applies, (c) the current failure rate estimate, distribution (such as Weibull parameter code), and life (such as 1000 hours to rising failure rate), (d) the MTTR, preventive maintenance fraction of stress time, and maintenance cost per 1000 hours, and (e) the approximate component cost, delivery, and weight.

With regular printouts of this nature, the design engineer is in a position to compare one part with another on a truly balanced and integrated basis, relying less on intuition.

The Bureau engineer, in evaluating competitive contractors, will know that the contractor who has such a system is making the most of data feedback to design, and that is equivalent to high-reliability design the first time.

4.2 PROBLEM PARTS

Parts fail for many reasons. Three of them are (a) the part is bad, or does not meet its own specifications, (b) its specifications are wrong, and (c) it is improperly used, whether or not correctly specified. Part of the failure diagnosis job (Chapter 16) is to find out which for sure. In any case a running corrective action log should be kept (Chapter 21, section 8) until the problem is completely resolved.

If the verdict is reason (a) above, the part should be removed from the Design Data (Section 4.1 above) printout, or at least flagged thereon, until the problem is resolved. If it is reason (c) it should not be removed because it is not a defective part. The Bureau engineer should see that such procedures are used.

4.3 CRITICAL PARTS

A critical part may be defined as one whose failure would cause system failure. Note that in this case it is not a question of the reliability of the part itself, but rather only of how it is used. A preferred part of "perfect" reliability can be, and should be, a critical part. Unhappily many people persist in thinking of critical parts as undesirable, and there are instructions to "eliminate" them. This is nonsense, because whatever replaces them then becomes critical.

There are several specifications that require "special handling" (see section 7 below) for critical parts, for obvious reasons. Thus "critical parts lists" are required of the contractor. But since they only reflect how the part is used, and should not be affected by its inherent reliability, a given part will be critical in some systems and not in others.

"Criticality", on the other hand, is a number that expresses the effect of a given part upon system reliability. Thus its criticality is affected by both its inherent reliability and whether it is used in a manner that, if it fails, the system fails. All parts may be ranked in order of decreasing criticality, which amounts to a ranking of importance to system reliability achievement.

"Levels of Essentiality" have been established by BuShips Instruction 4410.17 for ships piping. Essentiality levels I and II are roughly equivalent to "critical" parts above. When the reliability and "essentiality" of ships piping are considered together, we are considering "criticality" of the piping.

The Bureau engineer should make sure that critical parts lists and criticality rankings are used when appropriate.

5. PARTS SPECIFICATION

Many of the contractor's design engineers may require the same part, and quite commonly its important characteristics are different for different applications. Thus if each design engineer writes his own specification, the parts manufacturer is confused by many inconsistent specs. The supplier is forced to form his own opinion of the relative importance of characteristics to standardize on only one or a few, to stay competitive.

But the contractors parts engineering specilists are in a far better position to evaluate relative importance of characteristics, or to talk the design engineer out of a specified characteristic that, on second thought, is not worth its cost. Or perhaps the specialists can suggest an alternative, for which the specification is already available.

Problems like these have led nearly all major contractors to establish centralized specification groups, with parts specification in the Parts Engineering group.

Many parts suppliers have embraced the word "reliability" without knowing what it means. Quite a few make "Hi-Rel" parts which may have a tighter quality control specification, but which actually promise nothing about the reliability or failure rate of the part. It's analogous to the small table model "Hi-Fi" radios which are not. The Bureau engineer must make very sure that parts reliability (failure rate, not quality) is specified.

A centralized contractor group responsible for writing all parts specifications can (a) contribute to standardization and its inherent reliability advantage, (b) write specs around at least two suppliers products to preserve competition (price and reliability), (c) use the widest possible knowledge of parts deficiencies across projects to influence spec revisions and new specs, (d) make sure that all necessary quality control requirements are included, and most importantly (e) see that maximum permissible failure rate, and the means of verification (including confidence level) is specified, but only to the level actually needed.

6. ENGINEERING STOCKROOM

A commonly-overlooked indirect source of unreliability is the engineering stockroom from which the design engineer or technician selects parts that "will work" in his mockup, breadboard, engineering model, or engineering prototype. At this design phase he is primarily interested in juggling parts and values until the mechanism or circuit functions in the manner desired. He has not yet tackled many constraints such as environment, tolerances, reliability, maintainability, parts delivery, cost, etc.

But once these parts are operational in the engineering model, most of them have a way of being specified in the parts list for release, and vociferously defended. To challenge them seems a reflection on the design engineer's judgment, and besides he is now too close to a scheduled completion to do much changing.

Many contractors avoid this problem by (a) having the parts engineering specialists control the stockroom inventory, (b) prohibiting non-preferred parts in the stockroom whenever an equivalent preferred part is available, (c) prohibiting the ordering of a non-preferred part in the same situation, and (d) having the parts engineering specialists review each design engineering request for new experimental parts, and order the "best" part (reliability and otherwise) with the design engineers concurrence.

7. PARTS HANDLING

The contractors manufacturing activity (and others to a lesser extent) handle millions of parts, and must do so in an economical and practical manner. Metal bins are widely used for "nuts and bolts" hardware. It was natural to use bins for electronic parts. While most parts can take the banging around they get from being poured into a bin, or dropped on the floor and tossed back, many cannot without degradation of reliability. For this reason, the Minuteman "high-reliability" parts program utilized rigid handling procedures.

There are many other opportunities for mishandling that cause reliability reduction. Examples are inadequate supplier shipping containers, rough treatment in receiving inspection, stacking large quantities with damage at the bottom, fatigue of parts leads by repeated bending during assembly, overheating of sensitive parts during soldering, overstress in factory tests, resting assemblies (such as circuit boards) on their parts while in factory transit, dropping assemblies on their parts, straining part leads or mountings by misalignment, etc.

Review of the above shows that some can be detected by quality inspection, but many cannot. The latter cause eventual failure due to operational vibration, temperature cycling, etc. Therefore much attention has been given to control of handling procedures to prevent reliability degradation. Since the parts engineering specialist is most knowledgable about the sensitive characteristics of each part, most contractors have made such specialists responsible for (a) the generation of control policy and procedures, for (b) review of engineering drawings and specifications to make sure they are invoked, and (c) review of factory and audit procedures to make sure they are invoked.

The Bureau engineer should make very sure that parts handling procedures are adequate and enforced.

8. TRACEABILITY

When a failure occurs in engineering or factory test or actual operation of a system, and failure diagnosis (Chapter 16) shows that the part and not its application is deficient, three steps become mandatory. They are (a) replace or repair the deficient part, (b) take steps to prevent receipt or use of any more such deficient parts, and (c) replace or repair any other such parts, now questionable, that may have been used anywhere in a manner that system failure could result. It is this third step that is complex and of concern here. For example, the use of welded instead of seamless drawn tubing on the Nautilus had to be traced.

The problem is to keep records in such a manner that critical parts (whose failure can cause system failure) can be traced back to an individual or lot test history, and conversely that all application of a questionable such part can be traced to the specific systems and components where it was used. If not arranged carefully this can result in substantial paperwork and cost beyond real justification. BuShips Instruction 4410.17 discusses such control. There are two basic techniques, both widely used:

8.1 LOT CONTROL

In writing its part specification, the parts engineering specialist requires the supplier to keep complete records of the tests (100% or sample) he conducts on each manufacturing lot during which absolutely no material or process change was made. If a change was made he must record it and start a new lot number. Then every part shipped to the contractor must be identified (either on the part or by accompanying paperwork) by its lot number, or the lot number of the batch or lot of parts. Then it is up to the contractor to handle them in such a way that the record for each serial-numbered assembly shows the lot numbers of its critical parts. Complete system records show the serial numbers of all assemblies.

8.2 SERIALIZATION

When parts undergo a special high-reliability manufacturing process, and are individually (100%) tested, and then used in very critical applications (part failure begets certain system failure), they are often given individual part serial numbers. This of course provides excellent traceability, but requires a great deal of paperwork and high cost. It may be quite practical and effective for few-of-a-kind systems, but unjustifiable for substantial production, where lot control is a reasonable compromise

Another problem with part serialization is that many electronic parts are getting too small to hold a number, so the numbers are printed alongside them on a card used by the supplier to protect and ship them. Disassociation between card and part inevitably occurs.

Serialization is of course very widely practiced at the component, subsystem and system level, for roughly the same purpose, and is very effective.

8.3 CONTROL

Since lot or serial number instruction must appear on the part specification to the supplier, as well as on release paperwork to manufacturing, it is usually a parts engineering responsibility to develop practical traceability policy and procedures. The Bureau engineer must make sure they are adequate and enforced.

9. PARTS TESTING

Chapter 11 develops the techniques for verifying reliability. The standard MTBF test ("sequential life test" in the language of statistics) can work very well for most components, subsystems and systems, depending upon the importance of reliability and the economics of proving it. For some parts it works well, and for others it is impractical.

Today's part failure rates run the order of 0.002 to 1.0 failures per million hours of stress, which is 1 million to 500 million hours MTBF. If 1000 of each part is life-tested to 10-times-MTBF, the test durations will run 1.1 to 570 years. Obviously the higher the part reliability the more impossible it is to test for it. They become obsolete long before they can be verified. And the test investment is not justifiable.

Standardization on certain preferred parts by the contractor, and particularly if many contractors can agree on such preferred parts, permits a good supplier to greatly increase his volume of each of fewer parts. Thus he can justify automatic equipment and life testing of parts that otherwise would remain unverified.

A very significant contribution to the parts testing problem is the Naval Ordnance Laboratory (NOL) Inter-Service Data Exchange Program (IDEP) which collects well-organized test data from many participating contractors, digests it, and issues periodic reports on file cards with microfilm inserts of the detailed reports. Contractors frequently find an IDEP test report sufficent to eliminate costly tests that would otherwise be required. The system works.

Knowledge of the above verification situation surrounding each part used in industry is generally highest in the contractor's Parts Engineering group. Therefore most contractors assign to them the responsibility to (a) determine what parts verification approach is best, (b) specifying the exact test procedure, (c) determine whether the supplier can best do it, (d) actually conduct the tests if the supplier should not, (e) interpret the test results for acceptance or rejection, and (f) work with the supplier on deficient parts. The Bureau engineer should make sure that such integration of reliability test activities is adequate.

10. SUMMARY

Although perfect parts do not assure perfect system reliability, the failure of any one of most parts of a system causes system failure. Therefore thorough engineering control of parts is essential to system reliability.

Most contractors have found a centralized Parts Engineering activity, with experts in specific kinds of parts, to be indispensable. This chapter has outlined the principal activities of such specialists, why they are needed, and what they contribute.

The basic contribution is establishment of preferred parts for use by all design engineers, and ample consultation and guidelines for part selection and application.

Parts data, particularly concerning reliability, is needed in concise form for design engineer decisions. Part specification, handled uniformly, pays off in reliability. Engineering stockroom control, parts handling procedures, traceability, and parts testing have become especially important as higher system reliability is required.

No amount of system design, analysis, and reliability production will bring high reliability unless there is controlled and adequate critical parts reliability. The Bureau engineer must assure himself that the contractors procedures and enforcement thereof are adequate for the reliability required.

11. REFERENCES

(1) American Standards Price List and Index, American Standards Association, Inc., 70 East 45th Street, New York 17, N. Y.

(2) Reliability Stress and Failure Rate Data for Electronic Equipment, MIL-Hdbk-217, 8 August 1962, Supt. of Documents.

(3) Failure Rate Data Handbook (FARADA) SP63-470, 1 June 1962,

U. S. Naval Ordnance Laboratory (BuWeps), Corona, Calif.

(4) Reliability Assurance Program for Established Reliability Parts, Military Specification MIL-R-38100 (USAF), 15 April 1963.

(5) Reliability and Components Handbook, Motorola, Inc., Scottsdale, Arizona, by F. E. Dreste, et.al., Revised 3-1-63

Chapter 19

SUPPLIER RELATIONSHIPS

Chapter 19

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In order to design and manufacture equipment and systems of known and controlled reliability and maintainability, the contractor must in turn know and control the reliability and maintainability of what he buys. His sources may be called vendors, distributors, suppliers, subcontractors, etc., but we use the broad word "suppliers" to mean all of them.

Since suppliers normally provide the bulk of deliverable hardware, it is imperative that BuShips reliability and maintainability requirements be passed on to suppliers appropriately. But that weasel word is a Pandora's box, because the depth of specification and control must vary widely with (a) the reliability and maintainability actually needed, (b) the gap, if any, between needs and state of the art, and (c) the design level (parts vs systems). Obviously a competent pipe manufacturer would not and should not hold still for a complex reliability and maintainability program plan of 15 tasks. Conversely a radar computer manufacturer had better expect to guarantee the MTBF and/or agree to a set of reliability and maintainability tasks.

While supplier quality control programs have been very well developed by many contractors, and some of these claim to control reliability, the fact is that very few actually get into the suppliers' design capability to achieve specified reliability and maintainability. And there is no other place to get it. Tight surveillance of a supplier's procedures and quality control can minimize reliability and maintainability degradation, but cannot assure design achievement thereof.

Chapter 22, Section 15, and Chapter 23, Sections 2 and 3 delineate the BuShips steps necessary to assure that the contractor establishes an adequate supplier control program.

1. SUPPLIER QUALIFICATION

Without going to the expense of a personal survey, contractors can find out quite a lot through the mail. So can BuShips, for that matter. Figures 19-3 and 19-4 show a 2-page questionnaire that will pretty well highlight what suppliers have done and are doing. Another page could be added suggesting that the supplier state what he is planning to do, but of course such words are cheap.

SUPPLIER QUESTIONAIRE

for Product Reliability & Maintainability Qualification

This questionaire is used for preliminary evaluation of vendor and subcontractor qualification to supply, to BuShips contractors, products that will meet BuShips quantitative reliability and maintainability (R&M) requirements. This means products whose mean time between failures (MTBF) or percent successful, and (where maintainable) whose mean time to restore (MTTR) can be established. Since different products (from parts to subsystems) and applications thereof (R&M needs) require varying levels of supplier R&M effort, the response of fully qualified suppliers is expected to depend thereon.

Suppliers legal name ______________________ Date __________

Address ______________________ Phone __________

GENERAL INFORMATION

Management current personnel names and titles:

General ______________ R & M (if any) ______________

Engineering ______________ Quality ______________

Supplier is a manufacturer ( ), regular dealer ( ), auth. agent ( ), contractor ( ), distrib. ( )

Business is ___% government, ____% commercial. Work is ____% engineering, ____% manufacturing

Primary products are: (add OTS for off-the-shelf products)

Number of employees total ________, including ______ engineering and currently ______ R&M (if any)

ENGINEERING CAPABILITY

Activity is _____% research, _____% development, _____% mfg. eng'g, _____% eval. testing, _____% mfg. test.

External engineering used is _____% for ______________ External testing used is _____% for ______________

Present engineering activity: Other engineering experience:

RELIABILITY & MAINTAINABILITY CAPABILITY

1. What products have you furnished on which your customer (give name & contract) required:

   a. Design to quantitative R&M & verification? ______________________

   b. Design to "higher" but unquantified R&M? ______________________

   c. Conduct of specified R&M tasks? ______________________

2. What R&M specifications, if any, have been contractually required? ______________________

____

3. Have you kept permanent records of your product failures from design ( ) through manufacture ( ), test ( ) and operational use ( ). Do the records show environment ( ), stress ( ), and accumulated operating time ( ). Have you conducted product life tests ( ) to obtain MTBF estimates? Enter "X" for "yes".

4. How many people are currently responsible for (more than for anything else) each activity:

a. R&M education ______	e. Desig review ______	i. Change control ______	m. Data control ______
b. Design for R&M ______	f. Parts control ______	j. Supplier control ______	n. R&M testing ______
c. R&M analysis ______	g. R&M reports ______	k. Quality control ______	o. R&M mgmt. ______
d. Human factors ______	h. Corr. action ______	l. Failure diag. ______	

   p. All engineering activities excluding any above ______

5. To what major organization function does the R&M group, if any, report? ______________________

6. At what design phases, if any, is formal design review conducted ______________________ ______________________, by whom ______________________, and is R&M signoff required? Yes ( ) No ( ).

7. Are analyses available on the effectiveness (performance capability, R&M, delivery) versus total cost (price and lifetime maintenance) to determine optimum design? Yes ( ) No ( ).

8. Are you willing to use contractors preferred parts of known reliability? Yes ( ) No ( ).

9. Are you willing to guarantee R&M based on mutually-agreed-upon tests? Yes ( ) No ( ).

This response is certified to be correct by: (name) ______________________ (title) ______________________

Mail the completed questionaire to ______________________

Such returned questionaires permit the contractor or BuShips to (a) eliminate obviously non-competitive suppliers, (b) select those to be considered (of which ultimately the serious contenders will be personally surveyed), and (c) determine about how much reliability and maintainability education and control he will have to do to get the required reliability and maintainability in supplier products.

2. SUPPLIER REQUIREMENT CRITERIA

Just as the contractors reliability and maintainability program is determined by the BuShips requirements as in chapter 23 sections 1, 2.1.1, 3.1, so must the supplier's reliability and maintainability program be determined by the contractors system or equipment reliability and maintainability requirements. The contractor had to apportion them as in chapter 6, and has determined what quantitative reliability and maintainability he must specify to suppliers. Chapter 22 section 15 details the BuShips instruction to contractors.

But not all specifications to suppliers need or can have such a quantitative requirement. Here are the factors to consider:

2.1 NEED

If the contractor is supplying to BuShips equipment whose failure would not have important consequences (maybe air conditioning equipment), BuShips would not specify quantitative reliability nor a reliability and maintainability program. So obviously neither would the contractor to his suppliers. Conversely failure of a system upon which a major operational task may depend (say the power supply for fire control) would require the contractor to apportion BuShips quantitative requirements to his suppliers.

2.2 TECHNOLOGY GAP

If the well-verified need is for a system of much higher reliability (say 100-to-1 MTBF improvement) than previously achieved, and this is not exactly uncommon, then the contractor can only get it by relatively heroic measures as outlined in chapter 13. But quite commonly it is a judicious choice between (a) redundancy of mode or components and (b) parts improvement, the latter being very expensive if not infeasible. But the redundancy can be within his own design using supplier components, or within the supplier components, or both. In any case he will most certainly have to specify quantitative reliability to his suppliers, to a much lower design level than would otherwise be justified.

2.3 CRITICALITY

If the contractors entire system has a certain anticipated failure rate (say 100 failures per million hours of operation), then a simple measure of the "criticality" of a component thereof is the increment of that system failure rate (say 2 failures per million hours) due to that component. If the component is used redundantly, its own failure rate would be higher (say 10 failures per million hours).

Now obviously a component of zero criticality (say a pilot light whose failure would not contribute to system failure rate) does not need a quantitative reliability specification, much less a reliability program. On the other hand components of high criticality (say a radar magnetron) demand quantitative reliability specification to suppliers if the contractor is to achieve and control his system reliability.

So the contractor must rank all components in the order of decreasing criticality, and there will be a place in the list below which quantitative reliability specification and/or reliability and maintainability programs cannot justify their cost and possible delivery delays. One way to locate this boundary is by trial and error, starting at a low value (in the above example, ask for supplier quotations based upon quantitative specification, verification, and/or control for all criticalities above 1 failure per million hours). Then as the supplier cost estimates thereof come in, adjust the boundary upward to an economically justified level (say 5 failures/million hours).

2.4 SUPPLIER EXPERIENCE

Quite commonly an excellent supplier will have had little or no experience with design for specified reliability. If he happens to be a sole source for the needed component, or all other sources are not interested in upgrading their capability, the contractor has no choice but to bring the selected supplier up to speed. In this case he will undoubtedly specify specific tasks to be done, to achieve a specified reliability and maintainability.

3. SPECIFICATIONS

It is very obvious that the supplier cannot be held contractually responsible for what the contractor failed to specify explicitly. And yet it is impossible to specify everything. The contractor has to select experienced and trustworthy suppliers and bank on their own desire to satisfy him in order to stay in business. But there are grey areas. If the contractor plans to use a suppliers product in a new way, the supplier cannot be expected to forsee the implications without detailed engineering attention to the application. This is particularly true of reliability and maintainability implications.

3.1 SUPPLIER SPECIFICATIONS

Most suppliers develop excellent specifications on their products. After studying such specs, and judging how well the supplier stays within his specs, customers then place orders by product (or catalog, model or part) number appearing on the spec. But the customer in so doing is taking a risk that (a) the product that he receives will not be within specs, (b) something not quantified in the spec, that the customer assumed would be acceptable, does not fit, and (c) the supplier has changed something that does not affect the spec, but does affect the customers application adversely. It is the last two points that often adversely affect reliability.

As a consequence, most contractors have developed internal rules that say concerning components of criticality above the boundary in 2.3 above, that (a) no critical component may be ordered by supplier product number alone, (b) the suppliers specification may be referenced if uniquely numbered and dated for each change thereof, or it may be copied, and (c) the contractors additional spec requirements, if any, must be stated, as outlined below.

3.2 CONTRACTOR SPECIFICATIONS

For best economy, delivery, and reliability of supplier products, it is always desirable to order what the supplier considers standard ("off-the-shelf"), which implies using only the suppliers specification. But this may or may not provide adequate reliability. Even if it does, the supplier may make a design change that he considers a real product improvement, but because of the way it is used by the contractor, reliability degration may result.

Therefore contractors may adopt internal rules that say in addition to those in 3.1 above, (a) list the actual application spec requirements, including reliability and maintainability, but excluding unnecessary feature or spec ranges that available products may possess, (b) use the supplier spec ranges and words wherever they fit the need very well, and identify them as supplier standard, and (c) call the suppliers attention to what, in his standard spec, is not needed. This will permit the supplier to consider tradeoffs with the things that are needed beyond his standard spec, resulting in minimum cost and delay.

3.3 DATA

Good suppliers are ready to do anything that is economically justified to improve their products in the eyes of their customers. Thus it is not difficult to convince most of them that there should be a two-way flow of data on their products. This does not refer to QC corrective action procedures when a suppliers product gives trouble in the contractors plant. It does refer to exchange of reliability and maintainability data.

The supplier should be requested to provide full reliability and maintainability data on the products that he is furnishing during the suppliers design and manufacture thereof, including data derived from other customer usage of such products. The data should include operating (stress) time or cycles, local environment and stress, failure rate (or % failed, if failure rate is not obtainable), and downtime and manhours per failure. Other data may also be appropriate for specific products.

In return for the above (perhaps at no extra cost) the contractor should agree to provide the same information to the suppliers on his products, throughout contractors design, manufacture, test, checkout, and operation. And if BuShips will provide such information to its prime contractor after delivery and contract completion, the contractor should agree to continue the information flow to suppliers. This is probably the most powerful means of assuring that successive supplier designs will have the required reliability and maintainability.

3.4 REQUEST FOR PROPOSAL

As contractors find it necessary to impose quantitative reliability and maintainability requirements on suppliers, and particularly as we enter the era of attention to cost-effective design, the simple specification to suppliers will no longer serve the purpose for many products. The contractor will not know what reliability and maintainability can be achieved until he tells a few suppliers what he wants, and asks for their well-considered formal proposals. Nor will he know what the desired reliability and maintainability may cost. But with such proposals he can trade off the achievable reliability and maintainability with cost, including consequent Ownership cost (see chapter 26), and decide what exactly to require of the supplier.

The content of a BuShips Request for Proposal (RFP) is covered in chapter 23 sections 2.1 and 3, and the principles are no different for a contractors RFP to suppliers. If the contractor for a fire-control system is subcontracting its radar/computer, he will probably use nearly all the elements of section 2.1 of chapter 23 including a comprehensive reliability and maintainability Program Plan. But if he is buying roller bearings, he may use a very simple RFP involving no Program Plan specification of "how" the supplier will achieve the desired reliability.

4. PROPOSAL EVALUATION

Again BuShips proposal evaluation is covered in chapter 23 section 4., and the principles are the same for contractor evaluation of supplier proposals. The contractor can use the same weight ratings that were used to evaluate his own RFP, or a different weight rating, according to the contractors judgment of relative contribution to reliability and maintainability.

5. SURVEYS

Most contractors have appropriate supplier survey procedures, usually conducted by the Quality Control group. However, most of these do not actually evaluate the suppliers capability to design for specified reliability and maintainability, but rather his "control" procedures.

The Supplier Questionaire in 1. above of course constitutes a preliminary survey, but it cannot generate enough confidence upon which to base a decision to place an order.

When the contractor has narrowed his decision down to a choice between say two suppliers of critical components, it is time to conduct person-to-person surveys of the two to aid in the final decisions. Chapter 24 section 6.1 discusses such BuShips surveys, and the same procedures can be used by contractors.

After placing an order with a supplier, the contractor shouid then conduct periodic surveys of his suppliers of critical components. The selection of suppliers to be surveyed and the frequency of surveys (usually every 6 to 12 months, or when the supplier has made a significant change of design, manufacturing method, or organization) depends upon the criticality of the component. Chapter 24 section 6.4 outlines the BuShips post-award surveys, and contractor procedures would be the same.

The next two pages show a Design Vendor Appraisal Summary form used by a major shipbuilder (1), following which are the detailed questions, pertinent to reliability and maintainability, used by the appraiser.

6. CONTRACT NEGOTIATION

Considering the necessity for the contractor to require specified reliability and maintainability from his suppliers of critical components, and the fact that he will want to pass along some of his BuShips incentive to his suppliers, there is likely to be more negotiation of supplier contracts than in the past. Basically he should be negotiating promised reliability and maintainability values vs. their cost, without trying to control the way in which the supplier gets there. But with the many excellent suppliers who have not yet had experience with the reliability and maintainability tasks needed to get there, the contractor must also negotiate tasks.

The BuShips contract negotiation principles are covered in chapter 23 section 2.4, and chapter 24 section 4. These can be appropriately interpreted for contractor use with suppliers.

7. SUPPLIER EVALUATION

After a contract is placed with a supplier, the contractor will need to check periodically whether the supplier is still on the track. For a substantial subcontract of a critical component this may involve monthly (a)review of the suppliers monthly prediction of reliability and maintainability based on design to date, (b) review of the quantitative requirements if predictions are not consistent therewith, (c) review of supplier progress on reliability and maintainability Program Plan tasks, particularly Corrective Action Log progress, (d) review of verification test results, and (e) a re-survey every 6 to 12 months of the suppliers capability.

VENDOR

COMMODITY

DESIGN
VENDOR APPRAISAL SUMMARY

DATE

PLEASE CHECK APPLICABLE BOX WHICH BEST DESCRIBES THIS VENDOR'S PERFORMANCE.

THIS COLUMN IS FOR PURCHASING USE ONLY

I. ENGINEERING

	0	1	2	3	4	SCORE
A. TECHNICAL ADEQUACY OF DESIGNS:	NO EXPERIENCE	VENDOR CONSTANTLY PROVES HIS LEADERSHIP IN EVALUATION OF ADEQUACY OF HIS DESIGN, IN SPECIFIC APPLICATIONS, FOR PERFORMANCE AND DURABILITY. DESIGN INDICATES CREATIVE ABILITY. SUPPORTING CALCULATIONS OR EXPERIENCE BACKGROUND READILY AVAILABLE TO EB DIVISION.	VENDOR'S DESIGNS ARE BASICALLY SOUND, BUT EVALUATION OF ADEQUACY OF PERFORMANCE AND DURABILITY REQUIRES MORE ATTENTION ON HIS PART TO ASSURE THE DESIGNED END RESULT. CALCULATIONS ARE LACKING IN RIGOR.	VENDOR RELIES ON OLD STAND-BY DESIGNS WITHOUT INCORPORATING IMPROVEMENTS TO SUIT LATEST REQUIREMENTS. LACKS IMAGINATION.	VENDOR DOES NOT APPLY HIS TALENTS. DESIGNS ARE POOR. EMPIRICAL OR OPINION BASIS IS NOT SUPPORTED BY CALCULATIONS OF ANALYTICAL EXPERIENCE.	
B. PRACTICABILITY OF DESIGNS	NO EXPERIENCE	VENDOR DESIGNS ARE PRACTICAL AND RELIABLE. SIMPLICITY IS MAINTAINED. ACCESSIBILITY PROBLEMS ABOARD SHIP ARE CONSIDERED AND FACTORED INTO THE DESIGN.	DESIGNS APPROACH RELIABILITY, SIMPLICITY, AND ACCESSIBILITY REQUIREMENTS. REQUIRED DEVIATIONS USUALLY ARE REMEDIED BY MINOR DESIGN MODIFICATIONS.	DESIGNS ARE LACKING IN RELIABILITY, SIMPLICITY AND ACCESSIBILITY. MAJOR IMPROVEMENTS ARE USUALLY NEEDED BEFORE REQUIREMENTS ARE MET.	VENDOR UNSATISFACTORY. DESIGNS ARE CONSISTENTLY POOR.	
C. SAFETY MARGIN OF DESIGNS	NO EXPERIENCE	NECESSARY FEATURES ARE BUILT INTO DESIGN TO ACCOMMODATE THE DESIRED DURABILITY OF A GIVEN UNIT. CONTROLS ON BUILD-UP OF TOLERANCES, PARTS INTERCHANGABILITY, AND SAFETY MARGIN ANALYSIS ARE GIVEN THOROUGH CONSIDERATION DURING DESIGN DEVELOPMENT.	VENDOR DOES NOT UNDERSTAND FULLY, OR HAS NOT ADJUSTED HIS ENGINEERING CONCEPTS IN LINE WITH, THE DESIGN FACTORS INHERENT IN SAFETY MARGINS, PARTS INTERCHANGABILITY, AND BUILD-UP OF TOLERANCE. HOWEVER, HE SHOWS INTEREST, CO-OPERATION, AND DEFINITE SIGNS OF IMPROVEMENT.	IMPROVEMENTS ARE SLOW IN MATERIALIZING. VENDOR IS RELUCTANT TO INVEST IN OR STRIVE TOWARD THE PERFORMANCE AND DURABILITY MARGINS SOUGHT.	VENDOR DOES NOT EVIDENCE EITHER INTEREST OR ABILITY IN MEETING EB DIVISION'S RELIABILITY STANDARDS.	
D. INITIATIVE IN PROPOSING IMPROVEMENTS	NO EXPERIENCE	VENDOR CONSTANTLY SEEKS TO UPGRADE HIS DESIGN PRACTICES; SHOWS LEADERSHIP TENDENCIES IN HIS FIELD. HIS IMPROVEMENTS ARE CONSISTENT WITH OVERALL QUALITY GOALS.	INADEQUATE COMMUNICATION FROM VENDOR TO BUYER RE: OVERALL QUALITY GOALS OR DESIGN REQUIREMENTS. HOWEVER VENDOR TAKES INITIATIVE TO IMPROVE UPON SHORTCOMINGS ONCE THEY ARE IDENTIFIED TO HIM.	VENDOR IMPROVES HIS DESIGN PRACTICES ONLY AFTER CONTINUOUS PRESSURE IS EXERTED ON HIM.	VENDOR TAKES NEGATIVE ATTITUDE TOWARD CHANGING DESIGN PRACTICES. PREFERS TO BE SATISFIED WITH THE "STATUS QUO". THIS BECOMES A "TAKE IT OR LEAVE IT" SITUATION.	
E. INITIATIVE IN COST REDUCTION THROUGH VALUE ANALYSIS	NO EXPERIENCE	ENGINEERING BACK-UP OF SALES OR SERVICE EFFORT IS IMAGINATIVE. VENDOR SHOWS INITIATIVE IN PROPOSING NEW IDEAS FOR REDUCING COST WHILE INCREASING HARDWARE PERFORMANCE AND DURABILITY.	IMAGINATIVE BACK-UP ON COST REDUCTION PROPOSALS IS LACKING OCCASIONALLY. NEEDS PRODDING WHEN VALUE ANALYSIS DATA IS REQUESTED.	COST REDUCTION BACK-UP IS INADEQUATE. VENDOR IS NOT ORIENTED TOWARD IMPROVEMENTS WHICH SIMULTANEOUSLY REDUCE COST.	VENDOR UNSATISFACTORY, APPARENTLY OBLIVIOUS TO VALUE ANALYSIS POSSIBILITIES.	
F. PROMPTNESS IN RESOLVING DESIGN PROBLEMS	NO EXPERIENCE	VENDOR RESOLVES OUTSTANDING PROBLEMS PROMPTLY REGARDLESS OF WHETHER THE RESPONSIBILITY IS HIS OR EB DIVISION'S. REQUESTS FOR VENDOR TO SUPPORT BASIC DESIGN DATA ARE COMPLIED WITH IMMEDIATELY.	VENDOR IS RESPONSIBLE FOR OCCASIONAL MINOR DELAYS IN RESOLVING TECHNICAL PROBLEMS.	VENDOR IS CONSISTENTLY UNABLE OR RELUCTANT TO RESOLVE TECHNICAL PROBLEMS PROMPTLY.	VENDOR UNSATISFACTORY. NO CHANGE NOTED AFTER HE HAS BEEN REQUESTED TO SPEED UP PROBLEM SOLVING.	

	0	1	2	3	4	THIS COLUMN IS FOR PURCHASING USE ONLY — SCORE
G. CO-OPERATION RE: NECESSARY DESIGN CHANGES						
	NO EXPERIENCE	CHANGE EVALUATIONS ARE PERFORMED DILIGENTLY WHEN MODIFICATIONS TO DESIGNS ARE REQUIRED. THIS INCLUDES MATERIAL SELECTION AND COMPATABILITY. VENDOR OFFERS SUGGESTIONS RE: FEASIBILITY AND PRACTICABILITY OF SUCH MODIFICATIONS. VENDOR IS NOT OPPORTUNIST ABOUT DEMANDING PRICE INCREASES ON CHANGE PRETEXT.	VENDOR SHOWS RELUCTANCE TO CHANGE DESIGNS. HE REQUIRES PRODDING BEFORE MODIFICATION EVALUATIONS ARE EXECUTED. CO-OPERATION IS SHOWN, BUT IS SLOW IN COMING. USUALLY DEMANDS EXTRA COMPENSATION.	MODIFICATION EVALUATIONS ARE POOR. VENDOR HAS POTENTIAL BUT NOT DESIRE TO UNDERTAKE DESIGN MODIFICATIONS. SEIZES ON MOST CHANGES AS OPPORTUNITY TO MAKE MONEY.	VENDOR WHOLLY UNCO-OPERATIVE RE: DESIGN MODIFICATIONS; EITHER NOT CAPABLE OR UNWILLING TO PERFORM TO STANDARDS REQUIRED. UTILIZES DESIGN CHANGE AS A TOOL FOR EXORBITANT INCREASED PRICE DEMANDS.	
H. ADHERENCE TO PURCHASE REQUIREMENTS, PLANS & SPECIFICATIONS						
	NO EXPERIENCE	ADHERES TO PURCHASE ORDER REQUIREMENTS AND SPECIFICATIONS. EVALUATES AND COMPARES THEM WITH SIMILAR COMPONENT HISTORIES. QUESTIONS AREAS OF UNCERTAINTY AND RESOLVES THEM IN SATISFACTORY MANNER. DISSEMINATION OF PURCHASE ORDER DOCUMENTS WITHIN THE VENDOR'S PLANT IS ADEQUATE.	LIVES UP TO APPLICABLE REQUIREMENTS WITH OCCASIONAL MINOR DEVIATIONS. VENDOR IS CO-OPERATIVE RE: THE RESOLUTION OF SUCH DEFICIENCIES. OCCASIONALLY FAILS TO TRANSMIT NECESSARY INSTRUCTIONS FROM BUYER TO AN EMPLOYEE WHO NEEDS THEM.	VIOLATES SPECIFICATION REQUIREMENTS UNILATERALLY. UNCO-OPERATIVE RE: THE RESOLUTION OF DISCREPANCIES. HOLDS P. O. DOCUMENTS IN OFFICE LEAVING SHOP OR OTHERS UNINFORMED OF DETAIL REQUIREMENTS.	VENDOR UNSATISFACTORY. NO IMPROVEMENT NOTED AFTER VENDOR WARNED ABOUT POOR CO-OPERATION. DOES NOT EVEN READ P. O. DOCUMENTS AND MAKES UNWARRANTED ASSUMPTIONS ABOUT WHAT'S IN THEM.	
I. DESIGN SERVICE						
	NO EXPERIENCE	VENDOR'S DESIGN EXPERTS REVIEW EB DIVISION PROBLEMS AS A GROUP. VENDOR HAS AN ADEQUATE ENGINEERING CHECKING PROCESS. FACTORS SUCH AS MAINTENANCE AND SPARE PARTS RECEIVE CAREFUL STUDY. SERVICE IS EXCELLENT.	ENGINEERS ARE CAPABLE BUT EXPERIENCE MINOR DIFFICULTIES RE: FORMING EVALUATIONS AND MAKING SOUND ENGINEERING DECISIONS. DEVOID OF PARTY LINE INSTRUCTION.	ENGINEERS ARE RELUCTANT OR UNABLE TO MAKE CONSISTENTLY SOUND EVALUATIONS AND TECHNICAL DECISIONS WHICH ARE SUPPORTED BY THEIR OWN MANAGEMENT.	ENGINEERING SERVICES ARE UNSATISFACTORY. VENDOR IS NOT CAPABLE OF DEMONSTRATING POSITIVE ACTION. MAINTENANCE AND SPARE PARTS RECOMMENDATIONS HAVE NO TECHNICAL BASIS.	
J. SALES ENGINEERING SERVICE						
	NO EXPERIENCE	VENDOR RESPONSE TO REQUESTS FOR INFORMATION IS PROMPT, COMPLETE, AND CORRECT.	SERVICE IS OCCASIONALLY DISORGANIZED CAUSING CONFUSION AND DELAYS.	SERVICE IS UNSATISFACTORY. INFORMATION FURNISHED IS REPEATEDLY INCOMPLETE, INCORRECT AND OR UNREASONABLY DELAYED.	NO CHANGE NOTED AFTER REQUESTS FOR IMPROVEMENTS WERE MADE.	
K. CO-OPERATION RE: SPECIFIC NON-DESTRUCTIVE TEST REQUIREMENTS						
	NO EXPERIENCE	INGENIOUS ABOUT SUGGESTING NEW AND BETTER WAYS OF TESTING FOR QUALITY AT MINIMAL EXPENSE TO BOTH PARTIES.	VENDOR EXPERIENCES DIFFICULTIES ATTEMPTING TO COMPLY WITH NDT REQUIREMENTS. CAUSES MINOR DELAYS.	VENDOR IS INEXPERIENCED IN QUALITY AND PROOF OF TEST REQUIREMENTS REQUIRED BY EB DIV.	VENDOR IS UNSATISFACTORY. HE IS NOT WILLING OR CAPABLE OF MEETING EB DIVISION NDT REQUIREMENTS.	
L. CO-OPERATION RE: SPECIFIC SUBMARINE APPLICATION REQUIREMENTS: LOW NOISE LEVEL REQUIREMENTS, MERCURY PROHIBITION, WEIGHT MONITORING, SHOCK DESIGN						
	NO EXPERIENCE	VENDOR DISPLAYS WILLINGNESS AND ABILITY TO COMPLY WITH SPECIAL ANALYTICAL OR TEST REQUIREMENTS. STAFFED WITH COMPETENT TEST AND ANALYSIS ENGINEERS. TEST FACILITIES ARE ADEQUATE. GIVES PROMPT IDENTIFICATION OF ANY DEVIATIONS FROM REQUIREMENTS.	VENDOR POSSESSES NECESSARY PERSONNEL AND FACILITIES, BUT HE EXPERIENCES OCCASIONAL DIFFICULTY IN MEETING REQUIREMENTS. TEST RESULTS INDICATE MARGINAL EQUIPMENT. ANALYSIS NOT COMPLETELY OBJECTIVE. OCCASIONALLY DEVIATES FROM REQUIREMENTS WITHOUT AUTHORIZATION.	ANALYSIS AND TEST RESULTS ARE FREQUENTLY MARGINAL. COMPONENTS REQUIRE REPAIR BEFORE THEY QUALIFY. UNAUTHORIZED DEVIATIONS OCCUR FREQUENTLY.	VENDOR UNSATISFACTORY. FACILITIES APPEAR TO BE INADEQUATE. APPLICABLE MIL-SPECS AND OR APPROVED TESTING PROCEDURES ARE NOT ADHERED TO. TEST RESULTS AND TECHNICAL ANALYSIS ARE REPEATEDLY POOR.	

CONSIDERING THE POSSIBILITY OF MAJOR AWARDS, PLEASE INDICATE YOUR ATTITUDE TOWARD DOING BUSINESS WITH THIS VENDOR

OUTSTANDING VENDOR	BETTER THAN MOST VENDORS	GENERALLY CAPABLE	CAPABLE BUT NEEDS PRODDING	HAS SHORTCOMINGS BUT IMPROVEMENTS NOTED	UNSATISFACTORY	TOTAL WEIGHT / AVERAGE WEIGHT
☐	☐	☐	☐	☐	☐	

REMARKS: Please support all serious criticisms with specific examples:

SIGNED ______________________
ENGINEER

APPRAISERS QUESTIONS FOR THE DESIGN VENDOR APPRAISAL SUMMARY

A. Technical Adequacy of Designs
1. What test and/or performance histories are gathered?
2. How rigorous are calculations for performance and strength disability?
3. How close to the state of the art?
4. What are the limiting feature of the design for durability?
5. Does vendor document TFR incidents? Are these available to (the contractor)?

B. Practicability of Designs
1. Vendor has reviewed his product's application to submarine system and environments?
2. Vendor has visited ships or mock-ups to confirm and concur adequacy of application in his opinion?
3. Is design simplicity exploited as a creativity characteristic? How is this developed?
4. How is durability and reliability judged?
5. How has vendor used the stated design targets for life expectancy? What technical proofs of compliance have been made?
6. Has vendor used maintainability as a design characteristic? How?
7. What accessibilities have been provided in the product? How is the physical space evaluated from a man/maintenance coordination in the ship environment?
8. Are special tools or alignment jigs or special sequential assembly checks required for tear down and repair?
9. What are the limiting wear and/or deterioration considerations?
10. What spare parts are proposed to suit continuity of performance expectations?
11. What repair schedule is designed to provide adequate preventative meaintenance for extended life?
12. What program of Design Review is proposed for what stages of design and manufacturing?
13. How will vendor invite (contractor) participation in Design Review?
14. What means are provided for proper material selection and continuity of pedigree?
15. What means are provided for assurance of design, material, and quality of second tier purchases?

C. Safety Margins
1. What performance margin exists over guaranteed rating?
2. What is the "worst case" or limiting parameter in estimating type of casualty on overload?

3. Is a failure analysis study made? What mode and mechanism contributes to failure?
4. Is there any test-to-failure data available?
5. What safety factors are standard practice?
6. Are safety margins calculated?
7. Can safety margin and performance margin be related to expected performance life? What is the limiting margin which degrades with operating time?
8. What Services (oil, water, grease, electricity, torque, etc.) variabilities can be tolerated within guarantee performance range?
9. Is a tolerance analysis accomplished?
10. What effects are expected if adverse tolerance buildups occur? Is there adjustment means?
11. What overall performance factors or ranges of variability are controlled by permanent or maintenance adjustments?
12. What areas of the design have the maximum risk to successful performance?
13. If vendor could afford to redesign and reschedule, what design changes would he make as improvements?

D. <u>Initiative in Proposing Improvements</u>
1. Will vendor orient Design Reviews toward improving design as well as justifying current work status?
2. Does vendor have the courage to make the effort required for significant improvement?

E. <u>Initiative in Cost Reduction Through Value Analysis</u>
1. Can the vendors evaluate cost-effectiveness and comparison evaluations on their products?

F. <u>Promptness</u>
1. Does vendor promptly accept responsibility for obvious faults even if evasion is available via strict interpretation of specs?

G. <u>Co-operation, etc.</u>
1. (a) Are material selections offered to (contractor) for agreement?
   (b) Are substitutions made without (contractor) knowledge?

I. <u>Design Service</u>
1. Does vendor use planned objective Design Review at the purchase order acceptance phase?
2. (a) How is maintainability, accessibility, producibility, "Inspectability" determined as early inputs to the designer?
   (b) How is maintainability related to realistic provisioning proposals at the design stage?

K. Cooperation, etc. Non-Destructive

1. (a) How carefully does vendor extract all information from required tests?
   (b) Does he attempt to vary performance parameters to determine overall variability criteria?
   (c) Does he consider extrapolation of performance with time?
   (d) Does vendor design and prepare a test plan?
   (e) Is (contractor) party to pre-approvals of testing arrangements?
2. (a) Are test results provided to Engineering/Design?
   (b) Are these results checked against those expected by Design Engineers?
   (c) Are differences evaluated and incorporated in technical data as lessons learned for future work?

For a relative small purchase order for a critical component already designed, and whose reliability is already well-established and adequate, the contractor would need only (a) periodic confirmation of the predicted reliability (which would be subject to data coming in from all the suppliers customers) and (d) review of verification test results prior to shipment.

The above review is accomplished by contractually-arranged monthly reports, reviewed in detail and analyzed by a contractor reliability and maintainability specialist. But such review must be supplemented by regular visits to the supplier for understanding of the problems and formal or informal audit of the suppliers methods.

8. SUPPLIER CONTROL

If the supplier is competent, and has agreed to furnish specified quantitative reliability and maintainability for his product, and his contract says he will not get paid if he does not meet the spec, no further controls should be necessary. A competent supplier will control himself, and the contractors actions should always try to get him to do so. Then the contractor need only watch and regularly evaluate the reports.

If the supplier of a new and untried design cannot agree to so guarantee reliability and maintainability, then there must be contractual agreement on the tasks the supplier will perform in his effort to achieve specified reliability and maintainability. In this case the contractor must also audit and control effort task performance, involving corrective action followup, all of which constitutes a much bigger job.

As the contractors design progresses, there will be unforseen changes in the need for reliability and maintainability, perhaps because contractor design improvement tradeoffs change the criticality of the supplier product. For example the contractor may decide to add an alternative mode of operation, which in turn reduces the dependency upon the suppliers component. Such changes of need can easily change the suppliers most cost-effective approach, so he should be immediately informed of them. A contract change may be appropriate.

But then there are inevitable supplier deficiencies in achievement of reliability and maintainability requirements, achievement of reliability and maintainability program tasks, schedule adherence, or excessive expenditure. It is then up to the contractor to (a) get the facts and thoroughly understand the problem, (b) require official supplier commitment on corrective action by a specified date, or (c) alter the requirement on the supplier to fit the unforseen contingency, and (d) possibly alter the contract.

9. SUMMARY

In this chapter we have reviewed the normal interface between the contractor and his suppliers, so far as reliability and maintainability management is concerned. Since such suppliers provide the bulk of the hardware that actually determines the contractors achieved reliability and maintainability, careful management of suppliers is mandatory.

Qualification of suppliers must be based upon their capability to design for specified reliability and maintainability, not just to document it. The reliability and maintainability requirements placed upon suppliers are determined by (a) the actual need for reliability and maintainability, (b) the technology gap, if any, (c) the criticality of the component within the contractors design, and (d) the suppliers experience with design for reliability and maintainability.

We have tried to emphasize that contractor ordering simply by supplier product number is a dangerous practice, and cannot be tolerated for critical components. Yet the contractor should not create new specification language and quantitative requirements, which add to both contractor and supplier costs, where the existing supplier specification language adequately ties it down.

We have also emphasized the urgent need for data exchange with suppliers, and that it should not entail extra cost.

Perhaps most important, the contractor must recognize that a competent supplier knows far more about his product, and what can be done to improve it, than the contractor. So if more reliability and maintainability is actually needed, the contractor must solicit supplier proposals to get a fix on what is achievable and what it costs.

Then in approaching the contract negotiation and agreement phase, and subsequent evaluation and control, the contractor should try for contracts that require minimum control. Economic incentives and penalties surrounding reliability and maintainability achievement are powerful medicine. If the needed supplier refuses to commit himself to such guarantees, he is asking for a lot of detailed and costly "over-the-shoulder" control of "how" he does his job.

10. REFERENCES

1. Design Vendor Appraisal Summary, (1. Engineering), General Dynamics/Electric Boat Division, Groton. Connecticut.

Chapter 2

MANUFACTURE AND OPERATION

Chapter 20

MANUFACTURE AND OPERATION

We have constantly reiterated the need to get the required reliability and maintainability into the design itself, long before release to manufacture. Nearly all other chapters are addressed to the techniques for doing so. And if it is not done, nothing we can do in manufacture (including "zero defects") or in operation of the system, can restore the lacking inherent reliability and maintainability.

On the other hand the manufacturing processes can and usually do degrade the reliability below that inherent in the design. They reduce the reliability from a negligible to a substantial amount depending upon (a) the care with which the design allows for manufacturing state-of-the-art capability, or the design "producibility", (b) the adequacy of quality control, and (c) the attention to the items discussed in this chapter, which may or may not be considered quality control tasks.

Quality Control has been basically concerned with (a) the control of manufacturing processes and procedures that can affect product quality, and (b) the inspection and test of hardware during manufacture, to catch and correct all defects that can be found by such methods. The bulk of the quality control procedures catch current defects, and those which "could" lead to operational trouble, rather than those involving reliability or an operational time to failure. However many contractors Quality Control groups today do conduct MTBF tests, constituting the contractors product reliability "measurement" function.

BuShips can make sure that the contractor controls reliability in manufacture by delineating in the specification or program plan the tasks given in chapter 22 section 16. Methods for audit and evaluation of such contractor effort is covered in chapter 24 section 5, to be carried out by InsMat, SupShips or other cognizant government representative as outlined in chapter 24 sec. 7.

In the following sections we will discuss those activities having an impact on reliability (operational continuity with time), excluding those involving only current defects, regardless of the contractors assignment of responsibility.

1. SUPPLIER CONTROL

Supplier reliability and maintainability relationships are discussed in detail in chapter 19. We will only reiterate what is said by its sections 5 and 7, that the conventional and excellent supplier quality control survey techniques seldom cover the suppliers design capability. But once the design is released to manufacture, supplier control is primarily a manufacturing responsibility, thus covered here.

The suppliers welding capability, of both machines and welders, can have a significant effect on reliability depending upon the design configuration and safety margin. In order to assure itself of that capability, the contractor will often "certify" the suppliers welders and machines, or require the supplier to do so.

Soldering capability has the same or higher impact on electronic equipment reliability certification of personnel again being used.

Radiographic, ultrasonic, and infrared inspection techniques, since they check the above fabrication and assembly methods, also usually require the same certification.

Corrective action control is discussed in chapters 21 section 8, and 22 section 13. Where reliability and maintainability can be affected, the contractor can require his supplier to use such a procedure.

Once the suppliers design is frozen and accepted by the contractor, absolutely no changes of design, materials, or manufacturing processes should be allowed without the contractors knowledge and approval. Many system failures have occurred because the supplier made a small change that in his honest judgment "obviously" improved his product, but he could not forsee that the contractors special manner of using the product could not tolerate the change.

Since the supplier should have much better testing facilities and knowledge of his own product, it is nearly always preferable and less expensive to have the supplier conduct all final acceptance tests, suitably witnessed by a contractor's representative. This especially applies to MTBF tests, because the supplier can get more product hours of test across several or many customers, with much higher confidence in the result.

Supplier packing and preservation of his product can have an effect on reliability, as discussed in chapter 18. The contractor must insist on adequate supplier precautions.

If for any reason reliability and maintainability tests are not conducted by the supplier, they can be conducted in the contractor's Receiving Test. However this decision should be part of an integrated test plan.

Some supplier products are perishable or subject to corrosion if not properly stored prior to use in the contractors manufacture. This often amounts to predictable reliability degradation, so protective measures are required both by supplier, in transit, and in the contractors plant.

Supplier data reporting is discussed in chapter 19 section 3.3, and 22 section 18. The contractor must require the supplier to provide stress time and failure data on all critical products (whose failure would cause the contractor's system failure).

Failure diagnosis must be required of the supplier for every failure of a critical product, as discussed in chapter 16 and chapter 22 section 17. It is usually much more effective and economical for him to do it than the contractor, and a good supplier knows he needs that knowledge to survive.

2. MANUFACTURING CONTROL

As outlined in the introduction to this chapter, we are attempting to focus on the activities directly affecting reliability and maintainability, and not attempting to cover all quality control activities.

2.1 CRITICAL ITEM HANDLING

Manufacturing reliability control begins with establishment of (a) the "critical" reliability items deserving of special attention, and (b) the characteristics of those items needing special controls. Special attention requires physical identification so that all personnel who see the hardware or its accompaning paperwork see instantly that it is "special". Since critical items also deserve special handling, one commonly used method is the use of covered tote trays of a distinctive color for all critical parts, the trays often containing foam plastic cutouts to support the component properly. But since such trays have also been found very effective for general material control, some other color can be used for non-critical items.

2.2 EQUIPMENT PROTECTION

In shipbuilding, as well as in most other large manufacturing activities, the contractor normally receives much Government-Furnished Equipment (GFE) and Contractor-Furnished Equipment (CFE) to be installed in the system. During the period that it is on hand, both awaiting and following its installation, there are many opportunities for reliability degradation unless preventive measures are taken. So that the Bureau may have a standard of comparison in evaluating contractors equipment protection procedures, Figures 20-6 and 20-7 show samples of excellent procedures established by a major shipbuilder.

2.3 FABRICATION AND ASSEMBLY INSPECTION

The kinds of things that degrade reliability (later failure in operation) are loose or overstressed hardware, insufficient thread engagement, lockwashers, poor solder joints, loose solder, lack of surface protection, inadequate clearances, wiring harness bending stress concentrations, inadequate support (vs. vibration and shock), improper materials, etc. Inspection of fabrication and assemblies is normally conducted by quality control, so-phased that each job matches inspector capabilities (so fatigue does not lead to poor coverage), and so that areas are inspected before being covered up by a next assembly of which they are a part. Obviously encapsulation, which clearly protects reliability, must follow detailed inspection.

2.4 NON-INSPECTABLE DEFECTS

Many defects that can degrade reliability cannot be detected by inspection. These particularly include the material processes, such as heat treatment (including inadvertent), welding, plating, etching, finishing, casting, etc. They are usually controlled by (a) rigid control of the procedure, personnel, and equipment by which the process is accomplished, (b) non-destructive tests such as radiographic, ultrasonic, and infrared, and (c) sample destructive tests to failure, which generates confidence only if there is never a failure at maximum operational stress.

Contamination can be a reliability-degrading defect impossible to inspect, and often difficult to test for. It often results in elaborate "clean rooms" and rigid cleanliness controls for both personnel and hardware.

EQUIPMENT PROTECTION INSTRUCTIONS

for GFE and CFE

Equipment Nuclear - GFE	Frequency Check Receipt to Installation	Installation To Delivery	Instruction
Heat Exchangers Emergency Cooling Fresh Water and Salt Water Non-Regenerative (Purification) Regenerative (Purification)	C-1	W-3 G-4 M-2	1. Upon receipt; cap and maintain in accordance with manufacturer's instructions. 2. When installed, inspect zincs for corrosion; replace if corroded. 3. When filled with water, sample, analyze and treat in accordance with paragraph 2.1.1.1. 4. Protect on shipboard with sheet metal covers in accordance with paragraph 2.1.1.5.
Steam Generator	W-1	W-1,3 C-2	1. Unless otherwise specified by manufacturer, maintain secondary side pressurized to 5 psig with nitrogen. 2. Dry lay up. Inspect for corrosion, cleanliness and moisture. Add desiccant if required by manufacturer's instructions. Use dynamic dehumidifying machine when specified by the manufacturer (paragraph 2.1.1.2). 3. Wet lay up. Check that vessel is filled up into vents with water. Sample, analyze and test in accordance with paragraph 2.1.1.1.
Pressure Vessels Demineralizer Pressurizer	C-1	W-2 G-3	1. Upon receipt, cap and maintain in accordance with manufacturer's instructions. 2. When filled with water, sample, analyze and treat in accordance with paragraph 2.1.1.1. 3. Protect on shipboard with sheet metal covers in accordance with paragraph 2.1.1.5.
Reactor Pressure Vessel	W-1 C-1	W-1	1. Maintain pressurized with nitrogen to 5 psig, or as per manufacturer's technical manual. Cover with plywood and herculite material to protect reactor and openings.
Pumps and Motors Booster Charging Core Removal Reactor Pressure Fresh Water Vacuum	W-1	W-1,3 M-2 G-4	1. Rotate pump shaft 1 1/4 turns manually. 2. Measure and record insulation resistance. 3. Insure that permanent or temporary heaters are energized, where applicable, in motors. 4. Protect on shipboard with sheet metal covers in accordance with paragraph 2.1.1.5.
Main Coolant Pumps & Motors	W-1 C-1	W-1,2 B-3,4 G-5	1. Maintain pump containers pressurized with nitrogen in accordance with manufacturer's instructions. 2. Maintain nitrogen purge of 1/2 to 1 cubic foot per hour, whenever pumps are dry. 3. When pumps are dry, manually rotate pump shaft every 15 days. Record breakaway and running torques. 4. When pumps are wet and coolant system is operable, energize pumps for 5 seconds every 15 days. 5. Pumps with stellite thrust shoes do not require turning or purging.
Valves Check 10" Hydraulically Operated 5" Main Coolant Stop 14"	G-1	G-1,2	1. After inspection, cover and protect from damage until installed in ship. 2. Protect on shipboard with sheet metal covers in accordance with paragraph 2.1.1.5.

EQUIPMENT PROTECTION INSTRUCTIONS

for GFE and CFE

Equipment	Frequency Check Installation To Delivery	Instructions
Weapon System Project		
General		1. Mechanical Equipment shall be protected with original covers, or equivalent to prevent damage or contamination by dirt. 2. Extreme care shall be exercised to prevent damage and/or contamination of muzzle hatch power cylinders, missile tube annular spaces, locking rings, and breather valves. 3. Moisture usually forms when a missile tube is pressurized and de-pressurized. To remove moisture purge with air or nitrogen. 4. Electro-Optical lenses except as otherwise noted, shall be cleaned with medical grade alcohol and lens tissue. Eye piece protective covers shall be kept in place at all times when not in use. Optical carts shall be purged with nitrogen when indicator turns white. 5. Lenses on optical carts and Photo Electric Auto Collimators (PEAC) shall not be cleaned: if dirty notify General Electric Representative. Extreme care shall be exercised to prevent pressure or shock to optical equipment; suitable warning signs shall be used where appropriate. Do not allow any grinding, welding or burning until lenses are protected with their covers secured in place.
Missile Control Center	G-1,2	1. Due to the sensitivity of the electronic equipment installed in this area, the MCC shall be air conditioned and so maintained, prior to operation tests. 2. The cleanliness of the compartment must be maintained free from all loose foreign material such as dust, metal particles, welding slag, etc.
Alignment Group MK 1, Mod. 2 (see paragraph 2.1.2.1.)		
MK 84 Fire Control Azimuth Error Indicator (Alignment Trolleys GFE) Guidance Capsule Handling (Trolley end Hoist (CFE))	M-1,3 Q-2	1. Purge trolleys when indicator turns white. 2. Lubricate as required. 3. Examine tapes for kinks, nicks, cracks, weld splatter burns, deformed teeth and worn areas. Replace tape if any of the above conditions are found.
MK I Mod 4 or 5 Alignment Trolley	D-1,2,3	1. Keep trolleys up and level at Stations 1 & 2. Note - At this point the power and signal cable is retracted, thus prevented from getting damaged. 2. Place covers on optical windows. 3. Keep all personnel off the trolley drive tapes and electrical connectors.

2.5 VIBRATION "TESTING"

Vibration "testing" is often used in production. Usually conducted as a much lower stress level than will be encountered operationally, it has quite consistently disclosed loose hardware or solder that were not detected by very thorough inspection. And frequently it turns up an inadequate support problem that design engineers could not foresee. On the other hand some designs are necessarily such that the life of some parts is a direct function of the time they are under vibrational stress. If such design cannot be avoided economically, such vibration "testing" must be limited in such a way that sufficient life remains when the component is delivered for operation. But blanket prohibition of vibration "testing" may in effect degrade reliability.

3. INTEGRATED TEST

If every part, assembly, component, subsystem, and system were individually tested for all parameters of importance, the cost and time for test would be prohibitive. Thus most contractors have developed what has come to be called an "integrated test plan". Its essence is to so plan all testing that (a) for economy any one part is tested only once or twice, (b) such testing is done soon enough that there is time for correction (including procurement lead time) of defects discovered before the component is needed for the next higher level assembly, and (c) the tests should reproduce true operational environments, stresses, and especially interfaces with all other components.

3.1 PERFORMANCE TESTING

To do all of the above is impossible, and to approach the best compromise is extremely complex. From standpoints (a) and (c) above, one should simply test the finally completed system through all its complete operational cycles and modes, loaded to operational stresses or higher, in combined temperature, humidity, vibration, shock and radiation environment, and perhaps corrosive or abrasive atmosphere, altitude, even weightlessness.

The best we can do for environment is to develop a matrix of operational modes vs. environmental contributors, and use engineering analysis and judgment to select the apparently worst combinations of environments that are achievable.

Then there are many components of a system, such as where redundancy is used, that would not be adequately tested by a complete system test. So we back off to a series of component tests that should be conducted as soon as complete for reason (b) above, but preferably with their contiguous components to detect interface problems, and preferably in full environment. Similarly some components require prior testing at the assembly level, and some assemblies demand prior part testing. But not all. Finally we emerge with an integrated test plan that constitutes the most economical and adequate testing, but it avoids duplicate testing of parts to the extent feasible.

3.2 RELIABILITY TESTING

Now let's turn to MTBF testing, a primary kind of reliability testing. The principles are discussed in chapter 11. Ideally we could run the completed system thru its operational modes, fully loaded, at full operational environment, for a long period of time, and note whether or how often it fai' . This is often done for systems such as a radar or a wing structure. But it can be impractical for other systems such as a ship or a launch vehicle because of the time and cost involved, and impractical for some few-of-a-kind extremely-high-reliability components such as microelectronic assemblies that would become obsolete before the first failure.

Thus it has become logical to keep records of the stress time and failures that components accumulate in engineering prototype, manufacturing, and final system tests, throughout the integrated test plan. When the system is shipped to the user we then have at least some data on its reliability, ranging from "x hours with no failures" (for an MTBF estimate with very low confidence) to an estimate of MTBF with good confidence if there were a dozen failures. Sometimes this technique is supplemented by a relatively short MTBF test as outlined above, to obtain reasonable confidence that the reliability is adequate.

On the other hand MTBF testing is impractical for some systems and components, particularly structures, because failures so rarely occur. As discussed in chapters 7, 11, and 13, the only feasible "reliability" test is one or more overstress tests to failure. Such tests to failure are normally accomplished during the design phase, as such a test after manufacture would normally be too late to have an impact on the design.

However many overstress tests not to failure, such as 1.5-times operating pressure tests, provide considerable confidence in the design strength and quality.

3.3 MAINTAINABILITY TESTING

Maintainability tests do not have the time and cost problem associated with reliability tests, so can nearly always be conducted. But the planning and design of such tests can be quite complex. Again it is desirable to conduct them on the complete system, this time surrounded by a mockup of its operational location. Most-likely failures are simulated and technicians (of skill and training matching the users technicians) timed to determine how fast they can find and fix the failure. But again some maintainability tests have to be conducted at lower component levels so that there will be time to make corrections as a result.

3.4 FAILURE DIAGNOSIS

At the risk of seeming to emphasize the point, since some contracts actually limit the number of diagnoses, absolutely every failure occurring during test must be diagnosed. Whenever the cause cannot be determined, the component is forever suspect. Many contractors follow a policy of scrapping every such component that is in a critical application.

4. DELIVERY AND INSTALLATION

4.1 PACKING AND PRESERVATION

Just as in section 1 above we were concerned about the supplier's packaging and preservation of completed systems and components sent to the contractor, the contractor must be at least equally careful about packing and preservation of completed systems and components sent to the installation site.

Many design engineers fail to realize that the temperature humidity, vibration, and especially shock encountered in a cross-country van or freight often far exceed the operational values to which he designed. But if it is not designed for these values, and sometimes it cannot be, it is up to the packing expert to install whatever protection and supports are needed. Failure to do so degrades reliability by overstressing components "almost" to failure, so that the later operational stress may complete the failure. And it is up to the design engineer to advise the packing expert about sensitive components.

When the system arrives at its operational site, there must be clear unpacking directions to avoid inadvertent damage. If the damage is not visible (say a wire almost broken within unbroken insulation) the reliability has been degraded.

4.2 INSTALLATION

Installation involves the same hazards to reliability as Packing and Preservation, in that very careful handling of many components may be required to prevent overstress and therefore hidden unreliability. Such equipment should be clearly labelled to attract attention, with handling instructions. Such procedures are not new, but consideration of the reliability (vs. operational time) implications will often result in additional handling and installation constraints.

4.3 CHECKOUT

Checkout is undertaken when installation is physically complete, normally done by technicians to instruction manuals, under the surveillance of one or more engineers very familiar with the system. Checkout offers many opportunities for reliability degradation. When the technicians screwdriver slips and jams into a mechanism, he may inspect it carefully and try working the mechanism. If it seems still to work (within his own framework of knowledge) he considers that the end of it. But it may have been overstressed, almost broken, misaligned, etc. in a way that he cannot see, and later fails when needed operationally. This is not uncommon. It happens all the time. And there is also the kind of man who knows he damaged it but does not report it. Of course the design should have been "foolproof" in the first place. Thus there must be very thorough indoctrination and training of technicians, emphasizing the consequences of any failure to report possible overstress, and there should be no punitive action for such reporting.

5. OPERATION AND MAINTENANCE

The opportunities for degradation of reliability and maintainability in operation and maintenance are enormous. The largest single cause of unreliability in operational systems is probably not the hardware at all, but human error. For some systems, such as large computer installations, it has been estimated that 40% of the downtime is due to human mistakes, although many of these are charged to hardware failure. People are well-intentioned, often careful and dedicated, but fallible. What can we do about it? As discussed in chapter 14 we must use people only for functions they can perform better than hardware, then design the hardware for compatibility with human capabilities and frailties. Then we have to thoroughly train and motivate them, showing the consequence of error.

5.1 SPARES

Spare components and their logistics of supply also have an impact on reliability and maintainability. Spares needed for preventive maintenance obviously degrade reliability if they are not available when needed. Spares needed for corrective maintenance after a failure obviously degrade operational maintainability (but not hardware maintainability by the current evolutionary definition) if they are not available to restore the system. Lack of either of course degrades system availability and effectiveness. The only solution to this is of course a complete maintenance policy and logistics program, which are beyond the scope of this course. The Bureau of Supplies and Accounts is vigorously attacking this problem under the METRI program.

5.2 "ABNORMAL" CONDITIONS

Systems are designed to operate within specified environmental and stress ranges, to utilize specified inputs, and to perform specified functions. But such specifications cannot always encompass what actually happens. Unforseen environments and stresses are sometimes applied, the inputs are sometimes far out of tolerance, or an attempt is made to perform a function beyond capability of the system. Such abnormal conditions are often not apparent in the paperwork when a "failed part" gets back to the tender or manufacturer. So the system contractor gets a "black eye" that he may not deserve. But the system itself is indeed unreliable in the real environment that was abnormal only in relation to an inadequate specification. Therefore it is important to make every effort to get the real situation into the original design requirements, and to report the real situation surrounding each failure.

5.3 MAINTENANCE

However, it is in maintenance that the primary operational unreliability is generated, and there are some unresolved problems. First there is the manufacturers recommended preventive maintenance schedule, which he has carefully worked out to achieve optimum reliability. Perhaps more often than not, such schedules are not followed by the user. The result is less reliability than that of which the component and system are capable. We can call this part of the human error, since the hardware is certainly performing to specification. Therefore the user should have mandatory maintenance procedures that require adherence to the manufacturers plan (as specified in the Navy manuals), and either enforce the procedures or depart from them only with conscious knowledge of the reliability consequences.

Second is the corrective maintenance, involving detection of malfunction, diagnosis, acquisition of spares, replacement or repair, checkout, and sometimes reload. Detection and diagnosis, and to a lesser extent repair and checkout, require certain skills that may or may not be available. Of course the hardware should be designed for maintenance with specified skill levels, but if the manpower and skill levels actually available are something less than specified, which often occurs, maintainability and therefore availability is degraded. Therefore the equipment must be designed for the real skill level available, and maintenance personnel thoroughly trained.

Third, and applicable to both preventive and corrective maintenance, is the reliability degradation due to maintenance errors. As discussed in section 4 above, when the technicians screwdriver slips and damages a mechanism (but he does not think it is damaged), or he accidentally shorts two electrical terminals which damages a transistor, or he plugs a connector into the wrong socket, or he uses the wrong replacement part, etc., -- all these fact-of-life occurrences do degrade reliability. And often very substantially. As stated in 4.3 above, there must be very thorough indoctrination and training of technicians, emphasizing the consequences of any failure to report and fix possible damage, and there should be no punitive action for so reporting.

5.4 DATA RECORDING

These human errors are very difficult to record, because of human reluctance to admit mistakes, and therefore difficult to get back to the design engineer so he can make the next design more foolproof. But it is almost as difficult, in spite of complete data collection systems, to get good operating stress time and failure data on truly defective failed parts. In both military and industrial systems (such as large leased computer systems where maintenance cost comes out of the manufacturer's pocket), it has been found that the maintenance technician often cannot effectively collect the required data. He is highly motivated, and properly, to "get the system going" again as fast as he can. In industry his pay raises may depend on this capability relative to his contemporaries.

On shipboard, during active use of the equipment, the same urgency obtains. Technicians are by regulation required to fill out the Electronic Equipment Failure Report on absolutely every electronic equipment failure. But (a) he is usually unable to record the stress time or cycles, but is asked to "estimate" them, (b) he seldom records human failure when it is the actual cause, (c) he often fails to recognize a failure as such, so it is not recorded, and (d) in times of urgency he may have to defer reporting until he has to guess what happened.

As a result, data reporting has been far from adequate for the design engineer to identify the needed design corrections. Non-electronic equipment failure reporting appears to be even less adequate.

The Navy Maintenance Management System (see chapter 9) has been developed and it should improve the situation, but further improvement is needed to incorporate human failure data.

6. SUMMARY

In this chapter we have briefly discussed the primary activities for reliability control, rather than "quality control", during the manufacturing phase. These are primarily supplier control, critical item handling, control of non-inspectable defects, vibration testing, integrated testing for reliability and maintainability, failure diagnosis, and careful packing and preservation.

Then we have discussed the practices during installation and checkout, followed by the activities during actual operation and maintenance. In this operational phase the primary factors affecting reliability and maintainability are spares, abnormal conditions, quality of preventive and corrective maintenance, and data recording.

We emphasize that a very substantial part of system unreliability is caused not by the hardware itself, but by the way it is used and maintained.

Chapter 21

CONTRACTOR ORGANIZATION

Chapter 21

CONTRACTOR ORGANIZATION

If the contractor produces what he contracts to produce, on time, and within cost, BuShips personnel need not be concerned with how the contractor organizes to do the job. Of course this is a "big if". But if BuShips cannot be sure the contractor will do, or knows how to do, his job, there is a temptation to tell him how. And the contractor, needing the contract, may accept such direction. Chapter 23 section 3.4 quotes the MIL STD 785 guidance.

But if BuShips tells him how to organize, BuShips is substituting its own judgment (remote from the problems of the contractor) for the judgment of the contractor, who is in a much better position to understand the resources and constraints unique to his operation. So it is always preferable, when feasible, to negotiate a contract with sufficient incentive that the contractor will be willing and able to organize properly to do the job. He may need suggestions from BuShips, but the decision has to be the contractors.

There are almost as many kinds of organization as there are contractors, and the same is largely true of their reliability and maintainability activities. Yet there are some fairly common patterns. In this chapter we will try to show the more "typical" patterns of organization for reliability and maintainability, but we cannot say that "most" contractors use any one pattern.

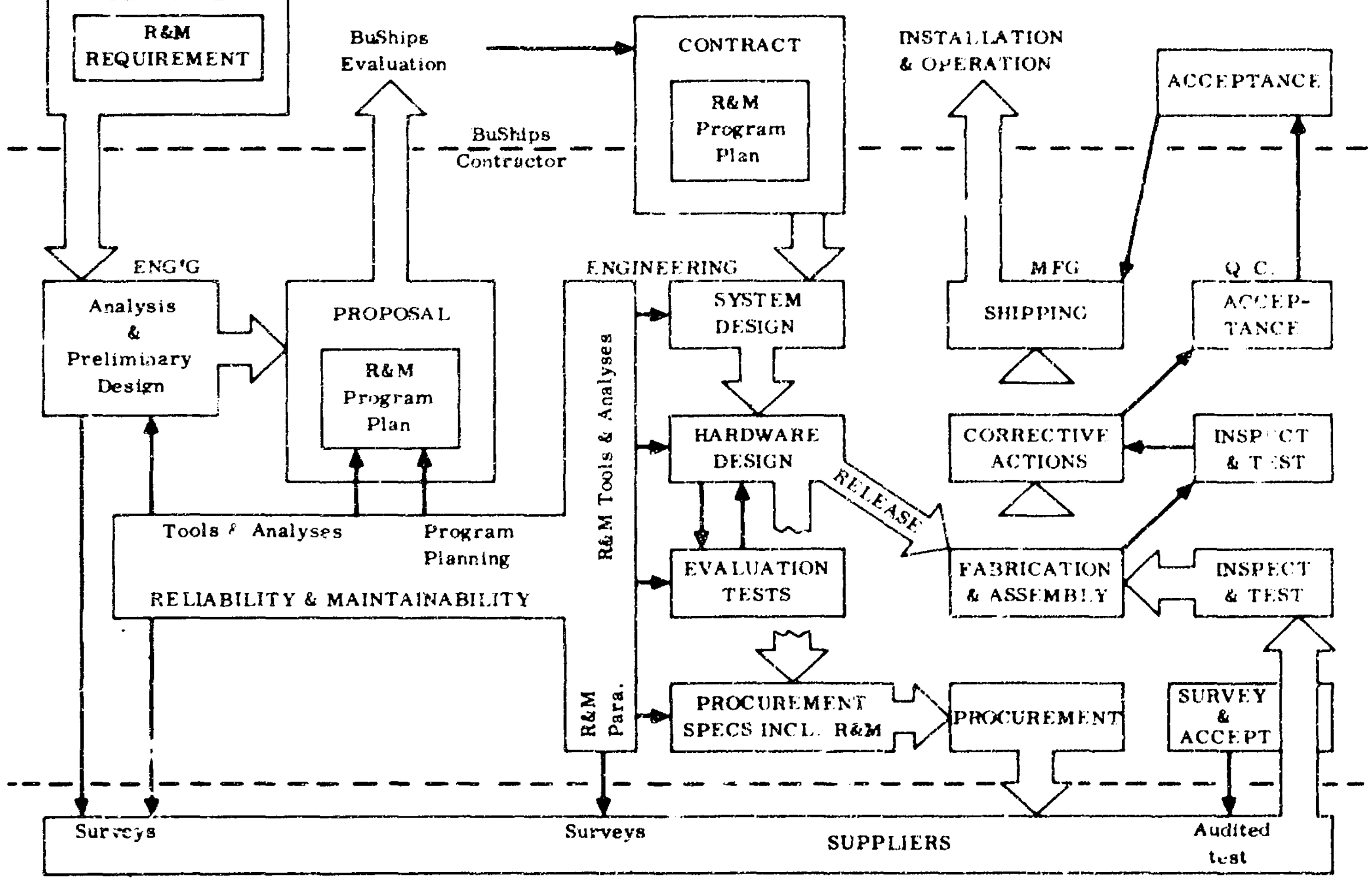
We are using the word "organization" in a broad sense, to mean how he arranges resources and work flow to get the job done, rather than the narrower "organization chart" sense.

1. WORK FLOW

Referring to figure 21-3, let us review the sequence for a large project. While this total work flow is given for illustration of the scope, most of the steps are required to some degree in nearly every contract. For example procurement of an off-the-shelf hardware item would not involve an RFP or system design. This chart does not imply any particular organization structure or jurisdiction of Reliability and Maintainability (R&M) groups.

The Request for Proposal (RFP) for a large project involving system design is thoroughly analyzed by an engineering group

CONTRACTORS WORK FLOW



(or an advanced systems group) to examine the requirements and feasibility. Feasibility can only be evaluated by considering alternative preliminary designs and selecting one that will be proposed. The contractors R&M specialists must provide (a) the necessary tools and techniques for analysis that accounts for reliability and maintainability, (b) the tools and techniques to design for required reliability and maintainability, and (c) may perform the analyses if they require techniques in which only they are experienced.

When the proposed design is established, a proposal is developed. The R&M Program Plan within the proposal is developed by the R&M specialists, working very closely with the design specialists. After BuShips evaluation and selection of a contractor, a contract is negotiated containing the negotiated R&M Program Plan.

Full system design then gets under way, using the tools and analyses provided by the R&M specialists, resulting in block diagrams, schematics, analytical models, and the detailed specifications that constitute the hardware design requirements. Detailed hardware design proceeds in the same way, this time involving evaluation tests of selected components or "breadboards", which tests require R&M specialist analysis. As design problems are resolved and component designs completed, detailed procurement specifications are written, and the R&M specialists may write the R&M requirements thereof. Component designs are "released" to manufacture as fast as they are completed.

Purchase orders on contracts, including the reliability and maintainability requirements, are issued to suppliers. As suppliers complete each major item, the contractor audits his final test thereof and accepts it for delivery. If for any reason it is not fully tested at the suppliers plant, or where components from different suppliers must be tested together, the contractor tests upon receipt. Fabrication and assembly then proceeds thru subassemblies, minor components, major components, and subsystems, testing as required along the way. As tests encounter problems, corrective action is executed, followed by retest of affected areas.

Finally the contractor determines to his own satisfaction that all specifications are met, and "accepts" it. The SupShips or Insmat representative, having audited the final inspection and test, accepts if he concurs. Then it is shipped for installation and operation.

Now let us refer back to the three levels of engineering design activities (Preliminary design, system design, hardware design). What, exactly, goes on in these blocks, so far as reliability and maintainability are concerned? The design cycle is shown in figure 21-6 to emphasize the highly iterative nature of design.

The design engineer must satisfy a surprisingly large number of requirements, including the R&M requirements, and do it within a surprising number of constraints, such as size and cost. To the extent he can calculate what the design should be, he is ahead. But in complex systems such pre-analysis bogs down in inability to think of, let along account for, all interfaces. So he resorts to trial and error on paper. Over and over, dozens or hundreds of times, until finally he has something that should do it. He uses analysis after each trial to evaluate whether his design meets all requirements and, if not, to point the way to a better solution.

So it is with reliability and maintainability. Starting with the R&M requirements, he first selects a design that he thinks will satisfy them, as well as all other requirements. Then he (or his R&M specialist) evaluates the design using the reliability apportionment/prediction techniques. If it is "not good" he uses the analysis to guide his next trial design. Then he goes around again until finally, perhaps weeks later, he works out a design that is "just right" and can be released to manufacture.

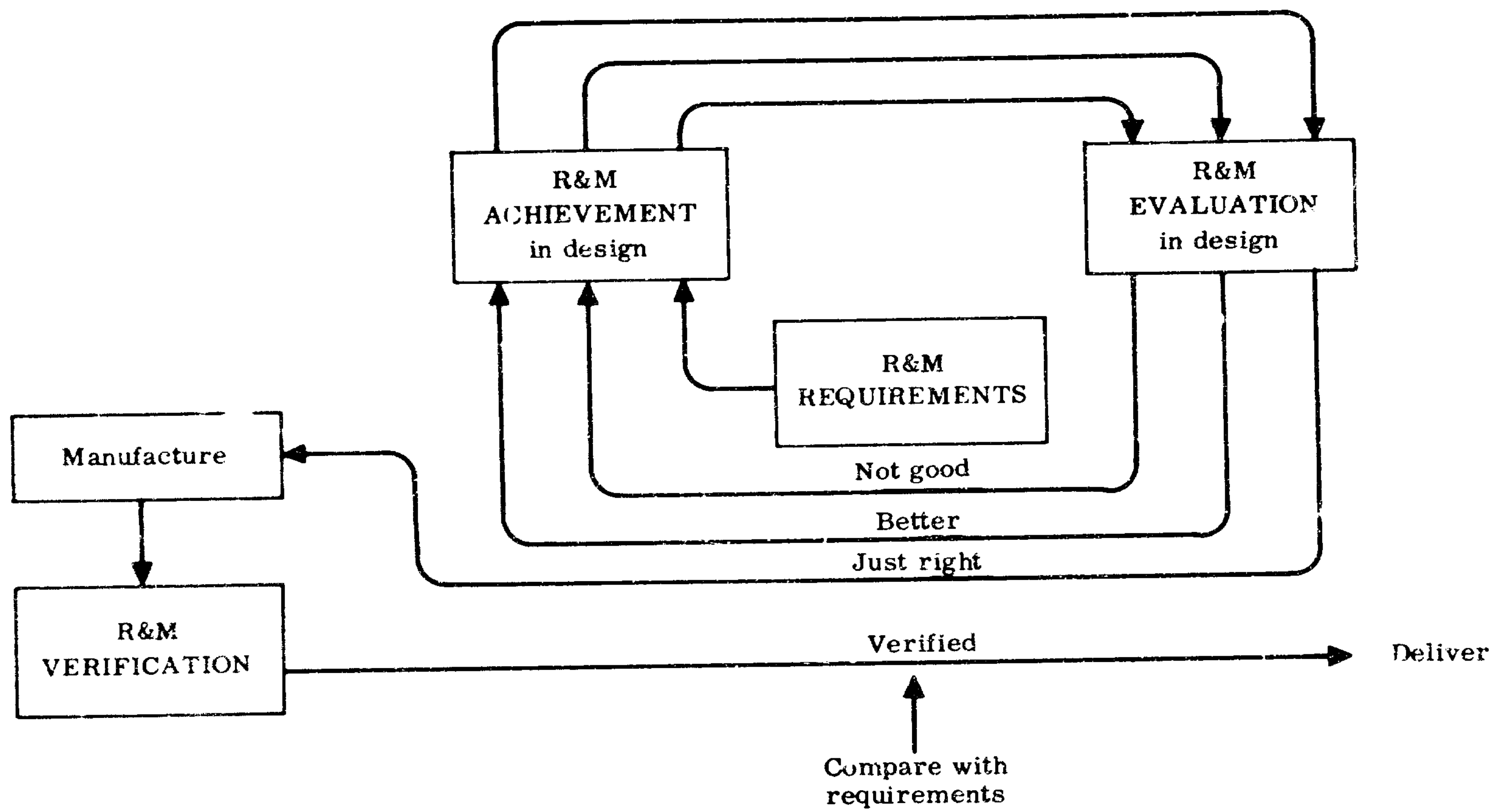
Now the point of all this is that, R&M achievement in design is the objective. This entire course has no other purpose. In order to achieve it, design evaluation (or analysis) is vital, but does not do any good by itself. Thus if the selected contractor has not organized in such a way that the design engineer achieves the required reliability and maintainability, then he does indeed need help.

2. ORGANIZATION STRUCTURE

2.1 FUNCTIONAL ORGANIZATION

Today we call the traditional organization structure a "functional" organization, meaning that the marketing, engineering, manufacturing, financial, etc. "functions" report to the top executive, and that all personnel report to one of these functional managers (or vice-president, director, etc.) according to their skills. It is a grouping by skills rather than projects. Functional organizations have the advantage of smoothing manpower requirements for each kind of skill, and therefore building and conser-

THE DESIGN CYCLE



ving knowledge and experience in each technology required, and profiting from cross-fertilization of ideas between experts.

Figure 21-8 shows the more common structural location of R&M groups in a functional organization. Pernaps the commonest and a very effective approach is an R&M group (by whatever name) reporting to the Engineering manager, giving it equal stature with all other engineering management activities. If Engineering then has major project groups, such as "Project A", the latter may either use the services of the top R&M group, or may in addition have its own R&M specialists or group. But if there is no policy-setting and technique-generating top engineering R&M group, one might question the effectiveness of the lower level project group.

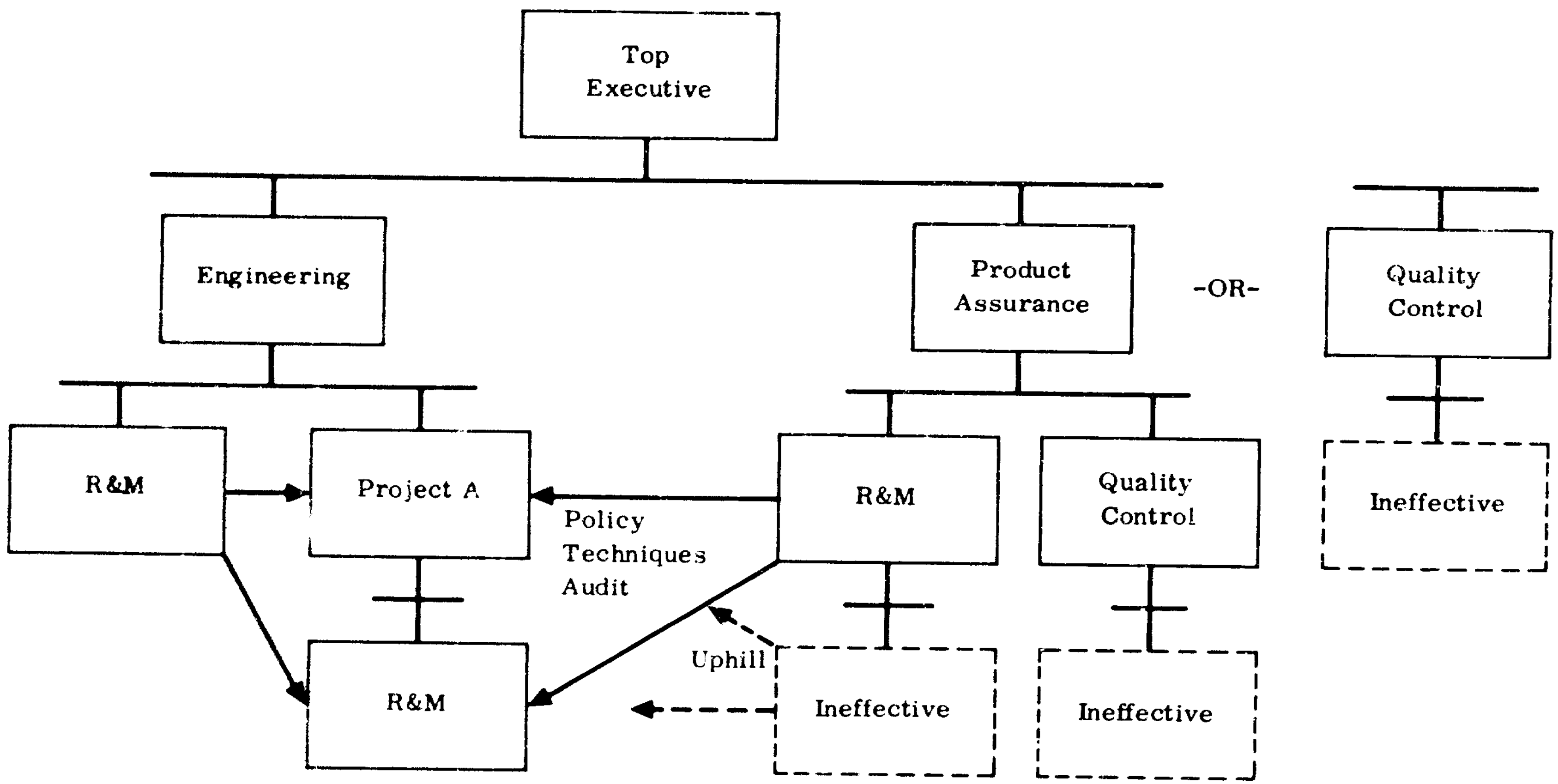
Many companies have established Product Assurance groups (also called by other names), reporting to the top executive, which essentially combine Quality Control and Reliability (rarely maintainability). This is an outgrowth of the Q.C. philosophy that reliability is "controlled" more than it is achieved by design. As a result, such groups commonly extrapolate the excellent quality control doctrines, techniques, viewpoints, and disciplines into design.

But this arrangement can work very well if the Engineering and Product Assurance managers actually understand the problem and actually support the R&M group technical activities. All too often this does not occur, and the design engineers have as little communication as possible with the R&M engineers.

Sometimes the R&M group is placed at the next lower echelon within Product Assurance, which makes it work "uphill" to the major Engineering groups. This does not work, because the R&M group is unable to get the "ear" of the principal engineering functions. Most experienced and competent R&M people know this situation only too well, so will not accept or stay in positions so structured.

Some contractors have tried to organize R&M as part of Quality Control, which demonstrates to knowledgable customers their lack of understanding of the meaning of reliability and maintainability achievement. The reason is that Quality Control commonly has many people labelled "engineers" who are not engineers at all, so competent design or R&M engineers fear associative damage to their professional stature and probably their salary. For the same reason the design engineering groups understandably resist

FUNCTIONAL ORGANIZATION



"control" (the QC philosophy) by people they consider unable to understand the design problem. Now this is a rather drastic simplification, but these situations do in fact adversely affect achievable reliability and maintainability.

2.2 PROJECT ORGANIZATION

One great disadvantage of at least a large functional organization structure is the tendency for any one project to get lost in it. There is little management of the project per se, schedules slip seriously before anyone is aware of it, and costs begin to rise. One solution to this problem is to have only projects reporting to the top executive, each project having its own independent functional organization. This does indeed manage each project much better, but results in little or no communication of technology across projects, gross duplication of effort, and very difficult manpower loading and turnover.

2.3 BALANCED ORGANIZATION

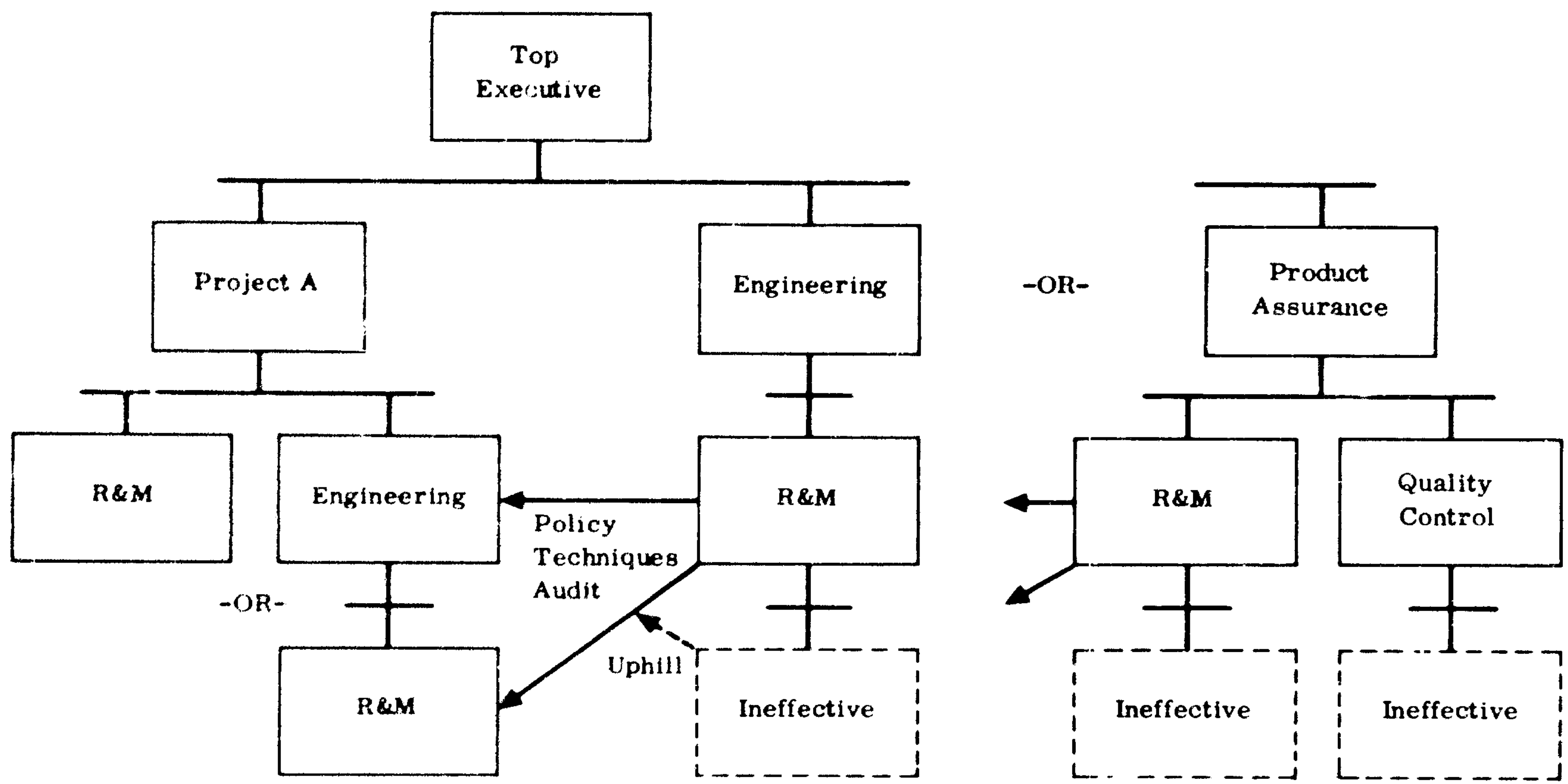
In attempts to find the best balance between the above two extremes, the "matrix", "hybrid" and many other schemes have been used. But the principal trend seems to be toward the balanced organization shown in figure 21-10. The general scheme is that both functional and project managers report to the top executive, which makes quite a management span for him.

Taking all engineering employees, for example, the central Engineering department is their "home", and responsible for hiring, salaries, and firing. The central Engineering organization maintains long-term centers of technology, such as R&M, where outstanding experts are located more or less permanently to develop techniques and provide consultation. Such an R&M group takes care of all R&M analysis and programs for new business.

When a project is formed as the result of a contract, the necessary engineering people transfer to the project for its duration, including R&M specialists. But the R&M policy and technique generation remains with the central organization, as well as the arrangement of regular meetings where R&M specialists keep each other up to date on techniques. At the conclusion of the project they are transferred back to their home group to work between projects.

In such a balanced organization the R&M group most commonly reports to the central Engineering manager as shown. Or it may

BALANCED ORGANIZATION



be called by broader names, such as Product Effectiveness, System Effectiveness, or Design Assurance. As discussed in 2.1 above, it would be ineffective operating "uphill" from a lower echelon.

"Project A" would have its own R&M (or another name) group reporting either to the Project manager (if R&M is a quite major consideration) or to the Project engineering manager in the commoner case. It then is on the same level with all major engineering groups of the project, which enables it to work well.

Alternatively the central R&M function may report to the central Product Assurance function if there is one. This is an uncommon arrangement, but can work if the Product Assurance, Engineering, Project A, and Project A Engineering managers all understand the problem and support the central R&M technical effort.

Again, as above, putting R&M in a lower tier or reporting to Quality Control does not work.

2.4 WHY SPECIALIZED GROUPS?

Many thoughtful managers question the need for special Reliability and Maintainability groups of specialists, and it's a legitimate question. If reliability and maintainability can be achieved only by the design engineer, then let's teach him how, and why do we need the specialists?

One reason is that the reliability and maintainability technologies are new, very fast-growing, generating a fantastic number of technical articles. If the design engineer tried to read all this material, to sift out what he needs or can use, he would have no time left to design anything. The specialist has to cover it, extract what is useful, then either use it or convert it to concise form for the design engineers.

Another reason is that although many of the techniques are well-developed, others are not, but urgently needed. Structural reliability prediction and hardware cost-effectiveness analysis are examples. The design engineer can seldom take time out to develop a new technique.

Another is that reliability and maintainability design and analysis is a small part of the design job. Many design groups could not justify a full-time reliability and maintainability specialist. The need for reliability and maintainability analysis is sporadic. In the interest of efficiency and technological continuity it makes more sense to establish a central "bank" of such capability upon which the design engineer can draw as he needs it (or upon which management can draw for audit). The widespread practice of establishing "stress analysis" groups is directly analogous.

And last but not least the establishment of a reliability and maintainability specialists group is probably the most effective way to get initial attention and action, as well as continuous emphasis. They won't let the design engineer overlook reliability and maintainability because of other pressures.

3. POLICY and PROCEDURE

A good-looking organization structure is worthless until there is clear and concise direction from management stating (a) what is to be done, (b) exactly who has the responsibility and authority to do it, and (c) how it is enforced.

Such policy direction concerning reliability and maintainability is usually issued by the top executive, by the Engineering executive, or by the Product Assurance executive. It makes little difference who issues it so long as all three really come to agreement and understanding on the subject.

Detailed interpretation of Policy is usually accomplished by Procedures written by the departments primarily concerned, carefully obtaining agreement of the affected departments. These include specific work flow between named departments, stating which department has responsibility and authority for what, and what standard documents are to be used.

There are some chronic problems with both policies and procedures, however, that may be of concern to BuShips when there is trouble with a contractor. Perhaps the worst offender is their issuance in such weasel-worded form that responsibility and authority are not actually pinned down. Sometimes this reflects honest difference of interpretation of the words, but all too often it reflects knowing compromise to the extent that the Policy or Procedure is meaningless.

Another problem is that while the document may be adequately concise, it is either not kept up to date or not enforced. Competent managements have established periodic audits to discover such discrepancies, and to either correct the document or arrange enforcement

Another serious problem is the tremendous flow of specifications out of government agencies, many of which conflict with each other. Each agency's representative has his own interpretation, leading to weasel-worded procedures to satisfy several conflicting masters.

Reliability and maintainability policies and procedures are particularly vulnerable to these problems because of the newness of the techniques to more contractors. If BuShips will state exactly what reliability and maintainability is required contractually, particularly if it is fixed price incentive, contractor management will quickly face the reality and decide exactly who does what to Willie.

4. RESPONSIBILITY ASSIGNMENT

Having established the importance of contractor assignment of responsibility, where should he assign it? Many of the tasks that have an important impact on reliability and maintainability, and which are called out in reliability and maintainability specs, do not belong in a Reliability and Maintainability group because of their much broader nature. Parts control is one of these. Design review is another, although often conducted by the Reliability and Maintainability group.

Figure 21-14 shows a fairly typical assignment of task responsibilities (a) between centralized functions and projects and (b) between design and Reliability and Maintainability engineering groups. Any one line across the chart represents a single principal task, as outlined in Chapter 22, but with modifiers in each column to indicate roughly what part of each is done where.

But again if there is contractor-wide recognition of exactly who is responsible for each task, and there is competent management, it makes little difference where it is done.

To go a step deeper, Figures 21-15 and 21-16 from (1) NAVSHIPS 94501 show a typical listing of tasks on the presumption that there will be Reliability Analysis, System Reliability, Parts Reliability, and Reliability Test groups. While this is an excellent organization (Federal Electric Corp), it is only one contractor. Most other contractors would have to do something differently to fit their own structures.

TYPICAL RESPONSIBILITY ASSIGNMENT

Centralized Engineering Functions		Project Engineering Functions	
Design	R&M	R&M	Design
	Customer R&M contacts	Project customer R&M	
	Proposal R&M, new projects	Project proposals	
	Industry committees	Industry participation	
	Contract R&M negotiation	Project R&M negotiation	
	R&D on R&M		
	Program Plan standards	Specific Program Plans	
Learn	Education	Refreshers	Learn
Design technology	Design R&M tools		Design to R&M
	Apportionment tools	Apportionment	
	Prediction tools	Prediction	
	*C-E analysis tools	C-E analysis	Tradeoff decisions
	FM&E analysis tools	FM&E analysis	FM&E decisions
Stress analysis	Stress/strength tools	Stress/strength analysis	Stress/strength design
	*Human factors tools	*Human factors analysis	Design for HF
Experts participate	Design review tools	Design review conduct	Participate
Parts control	Parts R&M data		
	Reporting system	Reports and review	Act on reports
	Action control system	Action control	Action
	*Change control system	*Change control	Change decisions
	*Supplier evaluation	*Supplier control	
	*Mfg. control system	*Mfg. control	
	*Failure test lab.	Failure diagnosis	Design action
	Data system operation	Data analysis	
Test laboratory	Verification tools	Verification control	Design action

*Often in specialist groups other than R&M

FUNCTION OF GROUPS

(Sheet 1 of 2)

	INITIAL DESIGN STUDY →	PRELIMINARY DESIGN →	DEVELOPMENTAL MODEL →	FINAL DESIGN →	PREPRODUCTION MODEL →	PRODUCTION →	FIELD OPERATION
Reliability Analysis Group	1. Develop and maintain reporting system.	1. Perform preliminary reliability prediction. Make recommendations to designers for reliabilizing circuitry. 2. Predict effects of manufacturing or parts variation on system performance.		1. Perform final reliability prediction. Make recommendations to designers for reliabilizing circuitry. 2. Utilize reliability reports from developmental model to provide statistical and engineering inputs for final design. 3. Assist designers in proper application of parts for circuitry.	1. Devise appropriate statistical techniques to provide necessary data from lab tests on preproduction model. 2. Establish samples and test plans for procurement specs.	1. Continuously assess factory test data. 2. Determine effects of manufacturing or parts variation on system performance. 3. Recommend corrective action after evaluating production and test reports. 4. Utilize reliability reports from preproduction model to provide statistical and engineering inputs for final design.	1. Provide engineer- and statistical analyses from field reports. 2. Recommend corrective action evaluating field reports. 3. Follow up the effects of modifications and changes.
Systems Reliability Group	1. Analyze specified requirements to assure initial design capable of meeting objective. 2. Perform study to determine optimized design conditions. 3. Assess effects of expected environmental extremes on system performance.	1. Determine effects of changes and modifications on system performance.	1. Make tradeoff decisions regarding size, weight, cost, schedule and reliability.	1. Assess effects of changes and modifications on system performance.	1. Prepare procurement specs to ensure that vendor parts and components meet subsystem requirements.	1. Evaluate recommendations for corrective action as to their effects on the overall system and make decisions as to their advisability.	1. Evaluate recommendations for corrective action as to their effects on the overall system and make decisions as to their advisability. 2. Evaluate effects of changes and modifications on system performance.

FUNCTION OF GROUPS

(Sheet 2 of 2)

	INITIAL DESIGN STUDY →	PRELIMINARY DESIGN →	DEVELOPMENTAL MODEL →	FINAL DESIGN →	PREPRODUCTION MODEL →	PRODUCTION →	FIELD OPERATION
Parts Reliability Group	1. Provide new parts data from literature.	1. Assist designers in proper application of parts.		1. Provide new parts data from literature. 2. Assist designers in proper application of parts.	1. Assess reliability of parts and components for engineering reference. 2. Establish liaison with and certify qualification of vendors. 3. Evaluate results of equipment tests, and investigate part malfunction. 4. Make recommendations concerning selection, procurement, and application of parts for the equipment.	1. Continuously assess reliability of parts. 2. Provide parts information concerning selection, procurement, and application necessary for corrective action.	1. Continuously assess reliability of parts 2. Provide part information concerning selection, procurement, and application necessary for corrective action.
Reliability Test Group	1. Plan the design of test fixtures and instrumentation required for meeting system objective.	1. Review and update the design of test fixtures and instrumentation required for meeting system objective.	1. Design environmental test fixtures. 2. Provide consultation on test plans to ensure meeting specified objectives. 3. Perform tests on developmental model.	1. Supervise installation of environmental test fixtures. 2. Provide consultation on test plans to ensure meeting specified objectives.	1. Perform environmental and reliability test on preproduction models. 2. Perform qualification tests on vendor parts.	1. Perform reliability sampling tests on production lots 2. Perform reliability sampling tests on vendor parts.	1. Perform tests to ascertain relationship between equipment performance and unexpected environmental conditions on input parameters.

5. EDUCATION AND MANUALS

As recognized by BuShips in its Procurement Request for this course, reliability and maintainability education has to begin with top management. Not a nickel will be spent, not an hour of work allocated for reliability and maintainability effort, until management can see why it's necessary. All too frequently, faced with the need to "do something" about reliability and maintainability, management will hire a reliability and maintainability "expert" and expect him to "take care of it." Without any cost, of course. It doesn't work, unless the expert somehow begins by educating management. And let's not be too hard on management. Part of management's job is to avoid spending money until convinced of the reason for it.

Then comes Engineering, and we mean the people who invent, create, and design the system, subsystems, and components to be manufactured or procured. Until all the contractors design engineers have some knowledge of reliability and maintainability achievement and analysis techniques, and some design engineers become real experts, management can hardly expect achievement in the design itself. And there is no other place to get reliability and maintainability.

One solution to this one is for management to establish a policy that at least one engineer in every design group takes a rather thorough reliability and maintainability course and becomes the group expert. Then he in turn can educate the group. Obviously this will not be effective unless the man chosen is one of the group's very best people, who enjoys the respect of the others in the group. And we said educate one of the existing people, who knows the group technologies, and not to add manpower.

And lastly, only because there is not much trouble with contractor management recognition of the need for it, there must be a core of reliability and maintainability specialists, who naturally must be well-educated in the technology. But since it is a very youthful technology, even in its infancy in some areas such as structures, it is a very fast-growing technology. Many new techniques are published each year, and the number of technical articles published is fantastic. The reliability and maintainability specialists must keep themselves up to date with the technology, and serve ideally to in turn keep the design engineers up to date on the techniques they use. And it is particularly important for them to train new hires, as few universities are doing anything about it.

But let's consider the design engineer. No matter how much we educate him in the theory and techniques, he cannot use them without the necessary tools. He cannot justify the time to research the literature. He cannot take the time to reduce a far-out mathematically complex theory to a simple equation that fits his problem. He cannot use the equation if he cannot lay his hands on applicable and convincing data to feed it. In short, his primary tools are very concise equations, tables, charts, specs, organized references, etc., that are convenient to use every day. So an educational program that does not concurrently provide the tools doesn't buy anything.

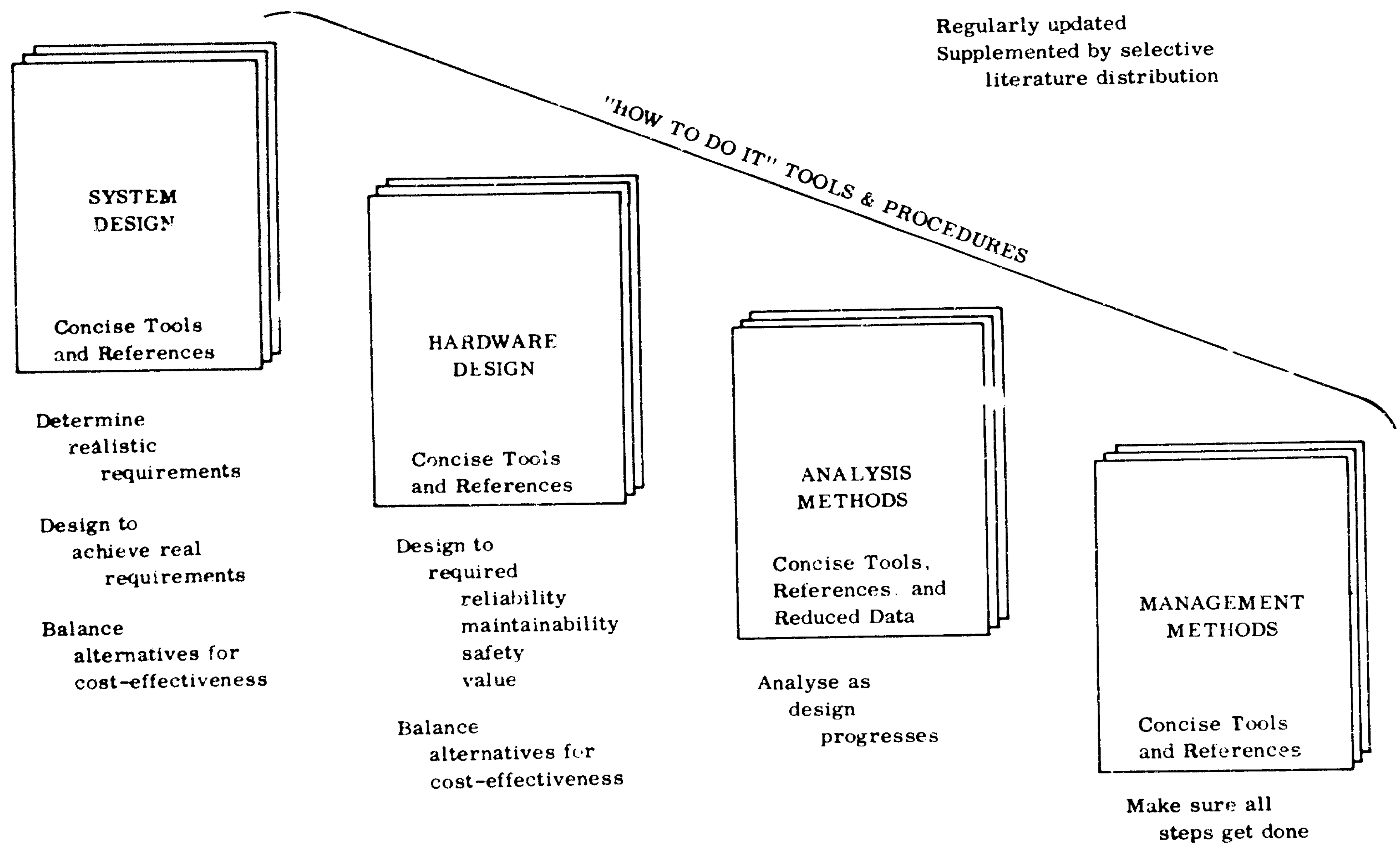
Figure 21-19 indicates the kinds of tools needed, which may be in the form of Reliability and Maintainability Manuals. And since the tools must be concise, there must be handy references to permit him to dig deeper into any specific aspect of importance to his design. But while we have discussed the design engineers problem, there is a corresponding need of the reliability and maintainability specialists for concise analysis tools. And there is a need of management for concise management tools. Figure 21-20 shows a typical standard content of Manual sections. Many contractors have developed "Reliability Manuals" roughly equivalent to this course. Relatively few contractors have developed manuals in a form really useful to design engineers.

6. TECHNOLOGY DEVELOPMENT

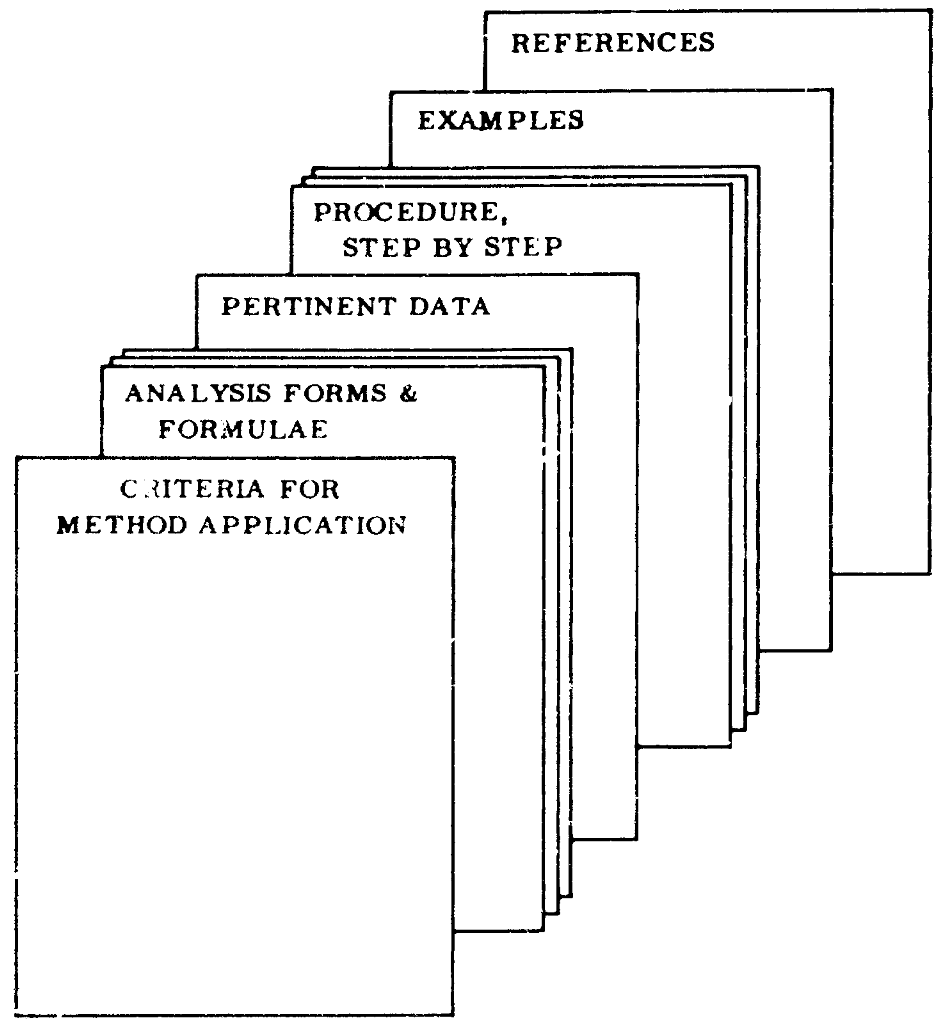
In Section 2.4 we mentioned that although many of the reliability and maintainability techniques are well-developed, others are not. Structural design to specified reliability needs a better approach. Data collection systems are still inadequate, though we know the data is obtainable. Design simplification techniques, based on reliability gain, are unexploited. Design for optimum redundancy (of mode, level, and kind) is still largely off the top of the design engineers head, rather than analytically logical. Cost-effectiveness criteria, for day-to-day use in hardware design, are undeveloped. There are many more examples.

Many small contracts have been let, by various government agencies, for the development of handbooks and specific techniques. Unfortunately most of these involve new documents or specific hardware analyses, as opposed to actual design achievement methods. And most of them are actually initiated by a contractor, and often the RFP is so worded that very few other contractors can understand the scope or propose to comply. There is a need for Bureau development of a reliability and

RELIABILITY AND MAINTAINABILITY MANUALS



TYPICAL MANUAL SECTION CONTENT



maintainability technology research program to take advantage of latent contractor specialized capability.

But most large contractors also conduct small reliability and maintainability technology development programs out of their own profits. A good example (2) is the development of a technique for cost-effectiveness ranking of design alternatives to determine optimal reliability and maintainability. This of course is done (a) to provide an advantage in the customers' eyes relative to the competition, (b) to provide more efficient (therefore, less costly) means of achieving required reliability and maintainability, and (c) to interest and hold top-notch people between projects.

Another very important contribution to the reliability and maintainability technology is contractor active participation in government committee efforts, industry-&-government committees, technical society conferences and symposia, etc. Next to actual application of a new technique, there is no better way to its development than trying to sell it to one's colleagues having diverse application backgrounds.

7. CHANGE CONTROL

Currently known by the fancier name "configuration management," change control is an old problem. It is the control of engineering design changes in such a way that all potential consequences are adequately considered before the change is released, and then the careful documentation and assurance that every consequence in design, procurement, manufacture, test, installation, operation, and maintenance is in fact handled properly.

Now change control is not normally a "reliability" matter, in the sense that an R&M group is responsible for it. But all too frequently, almost "normally," change decisions are made without adequate consideration of the reliability and maintainability consequences. And that makes it an important consideration in this course.

A good contractor will enforce change control procedures that prevent release of a change until its effect on (a) system reliability and maintainability, (b) reliability and maintainability acquisition cost, and (c) reliability and maintainability ownership cost have been evaluated and deemed acceptable.

8. CORRECTIVE ACTION CONTROL

The road to unreliability is paved with good intentions. Human nature being what it is, planned actions often get superseded or forgotten in the subsequent pressure of other needed actions.

Quality Control people have developed a technique, called Corrective Action Control, that very effectively prevents dropping a required action through the crack in the floor. It can be and is applied very effectively in engineering, especially for design review follow-up as discussed in Chapter 15, and failure diagnosis as discussed in Chapter 16.

Whenever a certain design or other action is decided upon, to achieve or preserve reliability and maintainability, it is given a number and title in a "Corrective Action Log." The log states very briefly what action is to be undertaken, and most importantly <u>who</u> is responsible for doing it. And a single name is more effective than shared responsibility. Then it shows a date by which time it is to be done.

The log is published weekly, distributed to those whose names are on it for action. When action does not occur in a reasonable time, a copy is distributed weekly to the delinquent's supervisor. The result is that people are periodically reminded of the due date, the action cannot be forgotten, and people like to get their names off the list.

Custody and distribution of the Corrective Action Log should be controlled by an independent group, so that items cannot be scratched until complete. For example, a decision to make a design change for higher reliability must result in one or more sequential Corrective Action Log items until the change is completely implemented. If it is already in production that means all retrofits installed and checked out, spares on hand, technical manuals changed, etc.

9. SUMMARY

In this chapter we have attempted to describe "typical" contractor organization to achieve the required reliability and maintainability. Work flow from receipt of an RFP to delivery of operating systems is shown in a gross way, though the details vary widely among contractors. In particular, the reiterative design cycle, alternating reliability and maintainability achievement and evaluation, is described.

Organization structure is important to BuShips only to assure itself that it is one of many that are effective. But an understanding of typical structures will also aid understanding and evaluation of proposals.

It is shown that there is usually good reason for specialized reliability and maintainability groups. The Bureau has recognized this and has started implementation in its organizations. The need for very clear policy, procedures, and responsibility assignment is emphasized, and typical allocations shown.

Education is even more effective to the contractor than to BuShips, and must encompass management, design engineers, and reliability and maintainability engineers. And education of design engineers is worthless without the day-to-day tools, or concise manuals.

Technology development, change control, and corrective action control are also discussed, as significant elements of the contractor's activities.

10. REFERENCES

1. Bureau of Ships Reliability Design Handbook, NAVSHIPS 94501, Fleet Electronics Effectiveness Branch, BuShips, March 29, 1963, Supt. of Documents.

2. Redundancy/Maintenance Cost Optimization for Manned Orbital Space Stations, by T. K. Jones, Aero-Space Division, The Boeing Company, Seattle, 15 July 1964.

Chapter 22

TASK DELINEATION

Chapter 22

TASK DELINEATION

Although there have been a dozen or so government specifications for reliability program management, DOD has consolidated these into one concise codument (1), MIL STD 785, based largely upon MIL R 27542A. It may be applied to all DOD military systems and their major subdivisions. However MIL R 22732B(SHIPS) is also available (2) for electronic equipment reliability and (3) MIL M 23313A for maintainability.

Like all concise top documents, it cannot go into the detailed requirements applicable to a specific system, thus is subject to differences of interpretation. For any one project or subsystem a given 785 paragraph may or may not make sense. And even when the paragraph applies, the depth or level of effort on it is subject to wide differences of opinion. So we must find ways to nail down exactly what is to be done.

To the contractor, the language of these specifications cuts across his normal organization structure. That is, he must translate it to tasks that he can assign to specific groups with clean lines of responsibility. It is in this translation that undetected misunderstandings and omissions occur.

For the BuShips engineer, these tasks constitute (a) the basic proposed work content to be included in the Technical Development Plan (TDP) and (b) the work to be specified to the contractor and monitored thereafter. Chapter 23 provides the TDP program language that integrates these tasks, including intended Bureau actions to assure successful completion of the tasks.

In this chapter we will quote those sections of 785 that result in specific contractor tasks, and then suggest for each any other language that may be used for more specific requirements. In addition there will be some tasks not directly called out by 785, but which experience shows are needed for large, and some small, projects. All such language applies to <u>major</u> projects, and the depth to which each task is needed, if at all, is discussed in chapter 23.

Finally, most of the tasks apply equally well to the achievement of required maintainability or availability. Since as yet there is no DOD maintainability standard, we have inserted the words "(and maintainability)" etc. as appropriate, in parentheses. It is suggested that the parentheses be removed when used for RFP instructions for the contractors reliability and maintainability Program Plan.

1. PROGRAM PLAN UPDATE

During contract negotiation many items will be dropped and added. After contractual authorization and during design and production there will be changes. Experience shows that consequent maintenance of the program plan as the current primary instrument of understanding between BuShips and the contractor is a substantial and important task.

> "The contractor shall prepare a firm reliability and maintainability Program Plan as a result of contract negotiation, and update it quarterly to agreed-upon changes."

2. EDUCATION and MANUALS

A primary deterrent to reliability and maintainability achievement is simple management and engineering lack of understanding of the problem and what to do about it. Very few, if any, of the contractors people have had such training in college. Some very competent contractors have trained some of their people; many very competent contractors have not trained any. Thus the "indoctrination" (of management) and training (of engineers) must be assured at the very inception of a program. See chapter 21. Otherwise there will be substantial resistance, inaction, redesign, excess cost, schedule slippage, and poor reliability and maintainability.

Actually this is part of a bigger problem (4) in that "half the knowledge of today's engineering graduate will be obsolete in a decade, and half of what he needs to know then has not yet been discovered." General Motors has a full-time faculty of 200. General Electric spends $45 million a year to support courses for 35,000 students. North American Aviation enrollment is 10,000 costing $4.5 million last year. Philosopher-mathematician Alfred North Whitehead says "Knowledge keeps no better than fish."

MIL STD 785 states (indented paragraph numbers henceforth are those of 785. If in parentheses it is a partial quote):

> "3.5.8 Reliability Indoctrination and Training. The reliability program shall contain provisions to supplement the basic training and indoctrination of company and plant personnel with reliability and maintainability training to assure

that their skills and knowledge keep pace with advancing technology and the requirements or peculiarities of the system or equipment."

Since the problem is often deeper than the contractor, these words may be added:

"The program shall provide for corresponding indoctrination and training of appropriate supplier personnel."

It is not enough to just lecture engineers on the technology, and give them references for further reading. The average design engineer will not begin to have the time, nor the patience, to research the voluminous literature to find what he needs for day-to-day design. It is essential that they be supplied with one or more very concise references manuals, wherein they can quickly find nearly everything they need to know day-to-day. These in turn can reference other literature for deeper specialized analysis. So the following may be added:

"The contractor shall provide one or more concise reliability and maintainability reference manuals, as well as the necessary data for common general use by all engineers on all projects. If necessary he shall provide them to suppliers."

3. <u>DESIGN TO SPECIFIED RELIABILITY AND MAINTAINABILITY</u>

Another major deterrent to reliability achievement is the general lack of design techniques in a form convenient to the design engineer for day-to-day use. As Rear Admiral Emerson Fawkes has stated (5):

"We must obtain a major advance in weapon reliability and maintainability. It is here that the greatest cost is experienced, and here that the greatest improvement in system effectiveness can be obtained. <u>A five or ten percent improvement is not enough</u>."

MIL STD 785 states:

(3.3.3) "The contractor shall identify specific technical problems to be solved, review problems considering program requirements, and develop a detailed program to solve the problems.....All designers and associated personnel shall be made aware of the reliability requirements pertaining to their area of responsibility and shall be included in the information loop to correct known deficiencies."

"3.5.3.1 Where estimates, data, and experience indicate a need for a parts reliability improvement program to achieve desired system reliability, the contractor shall propose a program to increase the standardization and reliability of parts to the required level."

"3.5.11 Maintainability. The effects of the reliability program on the maintainability of the design shall be considered during the initial and subsequent design phases to assure minimum degradation to system availability."

"3.5.12 Effects of Storage, Shelf-Life, Packaging, Transportation, Handling, and Maintenance. The contractor shall determine by test and analysis, or shall estimate, the effects of storage, shelf-life, packaging, transportation, handling and maintenance on the reliability of the product. He shall design the product to withstand these effects. Any special requirements or limitations on shelf-life, storage, packaging, transportation, handling, and maintenance shall be made known to the procuring activity."

The approaches that may be used to design to specified values of reliability and maintainability are discussed in chapter 13. Generally they involve (a) designing around (to eliminate or reduce criticality) the questionable component, (b) compensating for its deficiency via redundancy, etc., (c) improving it, (d) testing to find out more about it, etc. This is probably the most important single element of the program plan. But parts improvement is probably the most expensive and therefore the last resort:

"The reliability and maintainability program shall title and describe the anticipated reliability and maintainability design problems, with a statement of the data and component sources investigated and the logic of such identification. It will include situations where either (a) the available data indicates that state-of-the-art components cannot satisfy the requirements, or (b) there is insufficient known experience with the component to develop adequate confidence that it will meet the requirements."

"For each reliability problem above, the program shall state the design approaches to be used, considering as appropriate (a) simplication, (b) standardization, (c) parts selection and application, (d) stress/strength design, (e) tolerance evaluation, (f) failure rate prediction, (g) human engineering, (h) failure cause & effect avoidance, (i) preventive maintenance, (j) producibility, (k) supplier evaluation &

control, (l) evaluation tests, (m) local environment control, (n) failure prediction devices, (o) component integration, (p) redundancy, and (q) parts improvement."

"For each maintainability problem the program shall state the design approaches to be used, considering, as appropriate (a) simplication, (b) standardized design, (c) modular design, (d) adjustments, (e) failure effect provision, (f) accessibility, (g) safety, (h) evaluation tests, (i) identification, (j) total maintenance policy, and (k) failure detection and isolation devices."

"For each problem above, it shall state the test or other means of verification to be conducted to shown quantitatively that the design approach solves the problem, using only short one-or-two sentence statements that relate the problem to the overall Verification Plan below."

4. APPORTIONMENT

Apportionment of reliability and/or availability (accounting for maintainability) is the "budgeting" of the overall system requirement down to subsystem and component levels, so that individual design groups know what is required of their designs. It is done very approximately at first, then refined as the system model and prediction is developed. Ultimately the prediction and apportionment are (inversely) identical. See chapter 6. To the extent that design is accomplished within BuShips, so must the apportionment be accomplished by BuShips. The contractor, however, will nearly always have to apportion.

MIL STD 785 states:

(3.2.2) Apportionment of reliability and maintainability requirements from the system to system elements shall consider complexity and importance (effect of failure) of the system elements including alternative modes of operation."

"3.5.5 Mathematical Models. The contractor shall provide mathematical models based on systems analysis to apportion reliability and availability over major system elements; and to predict reliability and maintainability at various states of design. The mathematical models, apportionment, and initial prediction shall be included in the program plan."

Initial apportionment, if done right, can have a tremendous effect upon the design and cost of the system (such as choice of subsystems or components and decisions on redundancy needed), thus deserves some detailed attention. It also contributes to the comparison of competitive contractor designs and competence. These words may be used:

"The program plan shall provide a block diagram of the entire system system at least down to the subsystem level, and lower where feasible, showing on each block (a) its functional name and the apportioned (b) reliability, (c) criticality (contribution to system failure rate), (d) maintainability, and/or (e) availability that satisfies the overall system requirements. For simplicity he should where feasible use (for b & c) failure rate (per million hours), (for d) MTTR (hours per failure) and (for e) fraction of operating time, also showing (for f) manhours per failure. This will facilitate direct addition and visualization of the relative criticality of components. The contractor will fully explain the methods used for such apportionment."

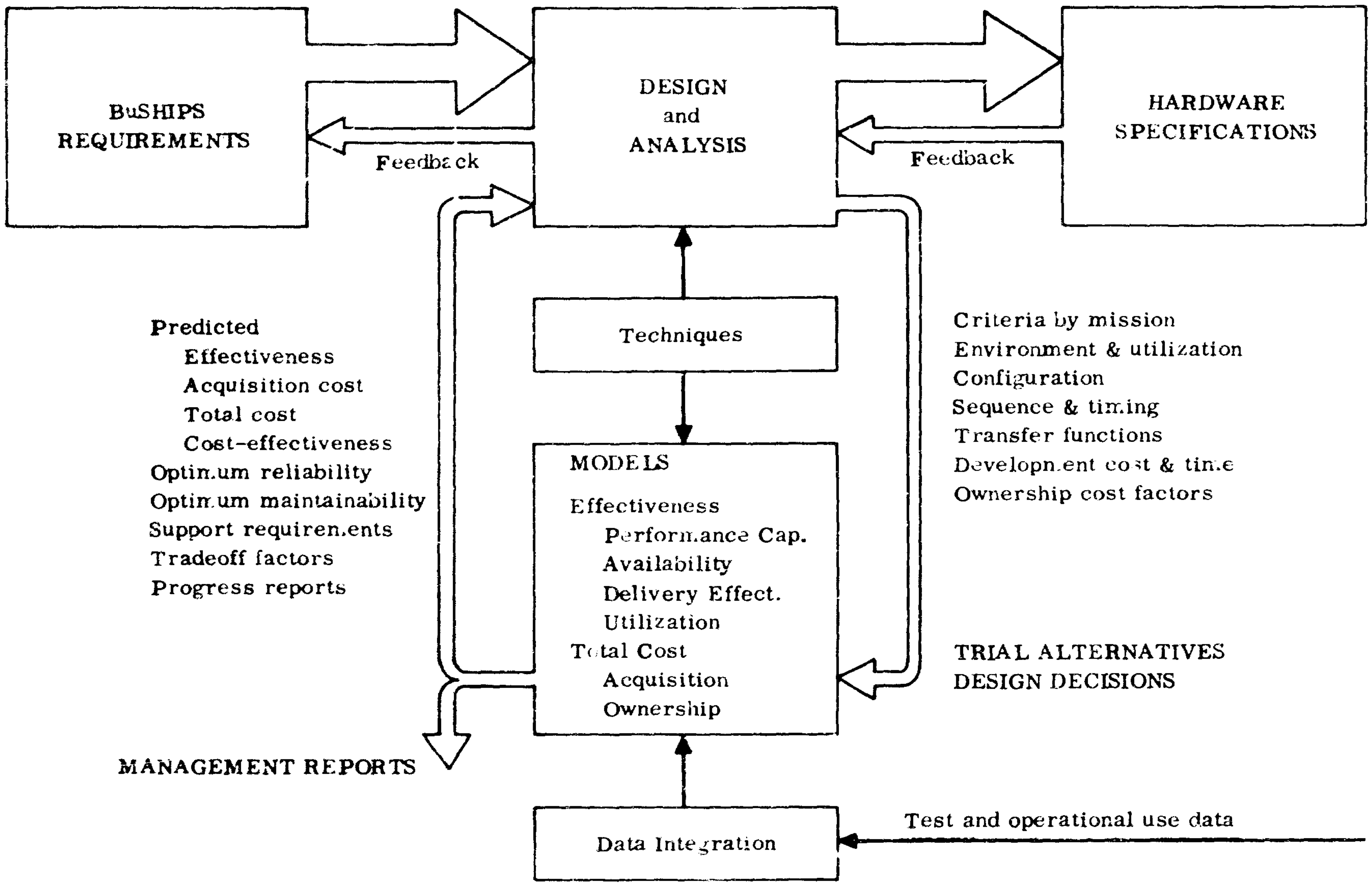
5. MODELS AND PREDICTION

As design progresses, a system analytical model is developed and refined to represent behavior of the ultimate system. When the anticipated reliability and maintainability of each system functional block is established, the model is thenceforth used to periodically predict system reliability and/or availability. Such models permit the design engineer to analytically test and decide between alternatives before commitment to production, and tell him where his design reliability or maintainability is not adequate, or may be too good. They also provide some management visibility of progress. See chapters 3 and 5, and figures 22-8 and 22-9.

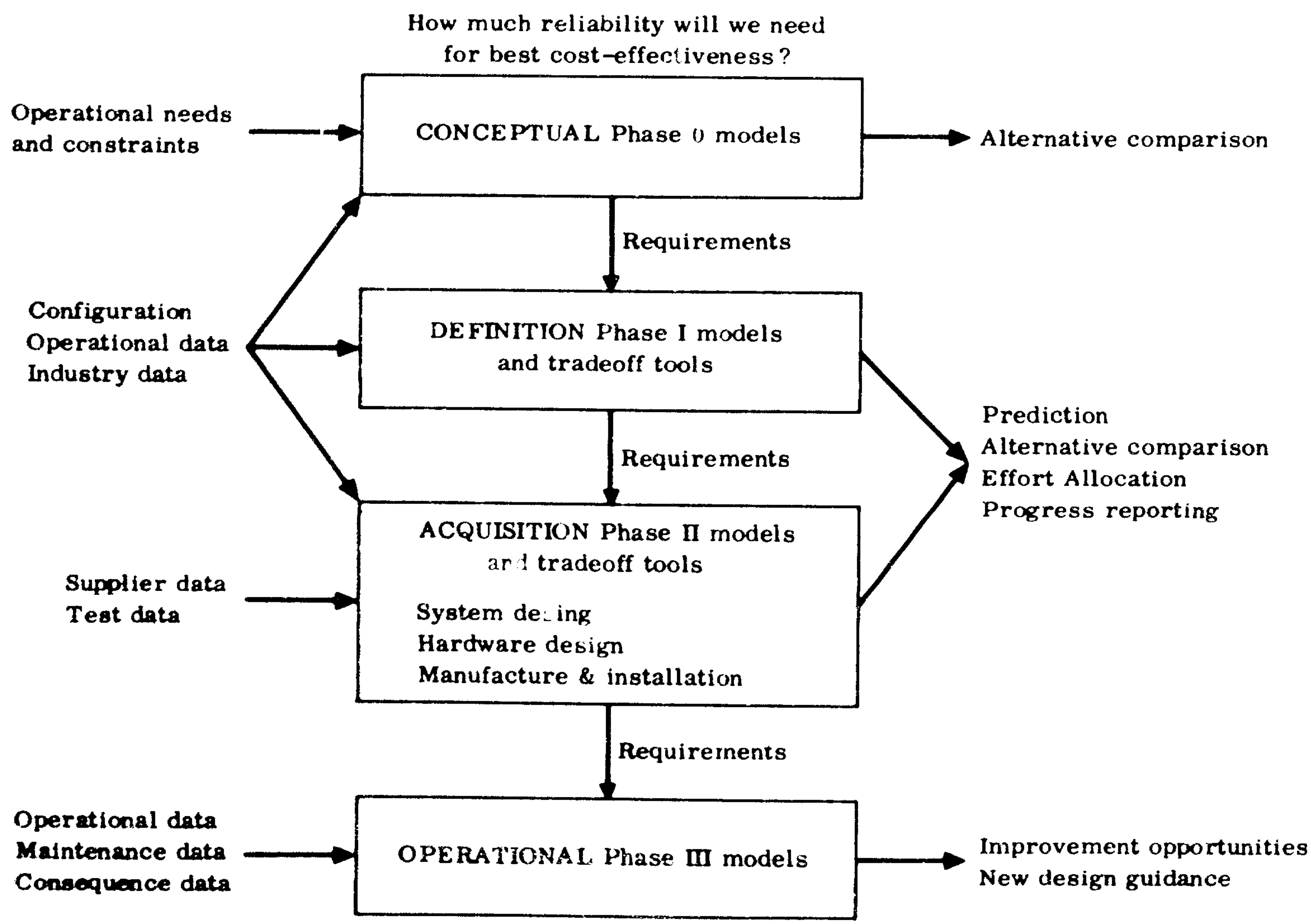
MIL STD 785 states:

"3.2.2 Reliability Requirement Studies. The reliability and maintainability program shall provide for preliminary and continuing studies of reliability and maintainability estimates and achievements. The reliability and maintainability program for all program phases shall provide for progressive refinement of the reliability and maintainability analysis and validation of specified requirements for all planned missions or operational modes of the system. These studies shall include definition of functional performance limits, duration of operation in time or cycles, etc., and the environmental conditions

THE MODEL LOOP



MODELS BY PROGRAM PHASE



of operational use. Apportionment of reliability and maintainability requirements from the system to system elements shall consider complexity and importance (effect of failure) of the system elements including alternative modes of operation. Progressive reliability and maintainability goals shall be established for each major phase of a program which are phased with program review points (3.4)."

"3.5.2 Furnished Equipment. Where other equipments, such as Government-furnished or associate contractor supplied equipment are to be integrated to provide a complete operational system, the contractor shall use known or estimated reliability values for these equipments. When such empirical data are not available through the channels to which the contractor has access, the contractor shall request such data from the procuring activity. The contractor shall report potential reliability problems introduced by deficient Government-furnished equipment or other associated equipment over which he has no control and shall indicate and justify the system changes necessary to accommodate or the improvement necessary to make this equipment compatible with the system requirements."

"3.5.5 Mathematical Models. The contractor shall provide mathematical models based on systems analysis to apportion reliability and availability over major system elements; and to predict reliability and maintainability at various stages of design. The mathematical models, apportionment, and initial prediction shall be included in the program plan."

Here again these techniques can have a powerful effect on the efficient and timely allocation of design effort, as they can show up potential deficiencies long before any metal is bent. For more detail these words can be used:

"The analytical functional model of the entire system shall permit (a) prediction of system operational availability and/or reliability, for each operational mode, as a function of its component reliabilities and maintainabilities, and conversely (b) assessment of component criticality (increment of system failure rate), and (c) prediction vs. apportionment of component reliability (failure rates where feasible) and maintainability (MTTR hours) and where feasible (d) manhours per failure. The model shall include human operators and maintenance personnel as components of the system, taking their reliability into account. The program plan shall fully explain the methods used to develop the model, and the procedures that will feed actual component data into the model

> as rapidly as it becomes obtainable, as well as estimates where necessary."

> "The model shall be kept current as design progresses. The contractor shall issue a monthly updated prediction of reliability, availability and/or maintainability, as appropriate, of the entire system, all subsystems, and all components. He will show current apportionment figures alongside each prediction figure, and highlight problems."

6. COST-EFFECTIVENESS ANALYSIS

Cost-Effectiveness analysis today is rarely required and infrequently used by contractors, -- at least by this name. But there is a growing need for its use, as discussed in chapter 26.

While such analyses are necessary to (a) establish requirements (chapter 23), they are also useful to (b) periodically re-examine requirements as design progress turns up unforeseen considerations, to (c) provide management visibility of progress, to (d) provide the design engineer with a day-to-day criterion for decisions (for example if thereby he knew that doubling the MTBF of his particular design would save $100,000 of total cost, he would be alert to such opportunities as he considers alternatives), and (e) provide a sound basis for supervisory allocation of design manpower according to potential payoff to BuShips and the contractor.

Cost-effectiveness analysis should not be confused with Value Engineering or Value Analysis. While these very important techniques have the same objectives, and contribute substantially to cost-effectiveness, their almost universal application (6,7) is limited to Acquisition Cost reduction of paper and assembled hardware designs.

MIL STD 785 has no provision for cost-effectiveness analysis. If it is desired, these words may be used:

> "The program plan shall provide for continuous update of the pre-contract cost-effectiveness analysis. The contractor shall issue a quarterly-updated (a) prediction of system cost-effectiveness, showing (b) the trend from prior predictions, and (c) the total cost saving, if any, that would result from 2-to-1 MTBF or MTTR improvement, for each subsystem and component."

7. FAILURE MODES & EFFECTS ANALYSIS

This is an old qualitative procedure that good engineers will say is done intuitively anyway. What is relatively recent, besides the name, is the meticulous and systematic detail. See chapter 12. If a reliability model is available, it should be able to predict quantitatively the effect of such failure modes. MIL STD 785 para. 3.5.6.1 (3) says only that "design review analysis shall include, to the extent applicable, analysis of effects of failure." But it is a widely-used worth-while tool. These words are recommended:

"The program plan shall include procedures for very systematic consideration of the significant ways in which critical (whose failure would cause system failure) components might fail, in relation to potential causes and effects. Such analyses shall be conducted during design, with appropriate design modifications to minimize adverse system effects, prior to design review and release to manufacture."

8. STRESS/STRENGTH ANALYSIS

When failure (time) rate data is not obtainable, as is often the case for mechanical and structural components, stress/strength analysis may be the only feasible method. However, it should be used wherever it is feasible, whether or not failure (time) rate data is available. Traditional stress/strength analysis using "safety factors" or "safety margins" is totally inadequate for achievement and prediction of reliability. Chapter 13 contains a design procedure and Chapter 7 the analysis techniques. Since MIL STD 785 has no provision for this method, these words may be used:

"For structures and other designs where feasible the contractor shall conduct stress/strength analyses that estimate reliability from the separation and variance of stress and strength distributions. He will then modify the design to provide adequate reliability."

9. HUMAN FACTORS

In quite a real sense <u>all</u> failures are traceable to human error, but unfortunately not all problems can be solved by the human factors "technology." Let's concentrate on a few quite significant areas. MIL STD 785 states:

"3.5.9 Human Engineering. The reliability program shall apply the principles of human engineering in all operations during design, development, manufacture, test, maintenance, and operation of the system or subsystem. The design shall incorporate human engineering features that minimize the possibility of degrading reliability through human error. Contractor's human engineering personnel shall participate in design activity and proposed tests to assure that the principles in MIL STD 803 have been incorporated in design and are reflected in test plans."

Since the "human engineering" phase normally does not include the human factors considerations in conceptual design discussed in chapter 14, the following may be added:

"The contractor shall analyse the functions required of the overall system and each subsystem, to determine whether the best effectiveness in relation to long-term cost (accounting for reliability and maintainability) is achieved with human or hardware components, and modify the design accordingly."

If further translation in terms of the specific contractor task is desired, the following words may be used:

"The contractor shall analyse the functions required of human operators vs. skill level available, to determine optimal display and control configuration and the achievable human reliability and maintainability, and adjust the design accordingly."

"The contractor shall analyse the functions required of maintenance personnel vs. skill level, spares, and facilities available, to determine optimal hardware configuration, diagnostic aids, and achievable restoration time, and adjust the design accordingly."

10. DESIGN REVIEW

Many design engineers resent the idea that anyone else should review and criticize their brain-child. Yet it is a fact that (a) no engineer can know all there is to know about all aspects, (b) often engineers, under schedule pressures, do not have time for adequate consideration of alternatives before proceeding with detail, (c) some engineers get so preoccupied with an "elegant" approach that they fail to see simpler approaches, and (d) hardly anything has ever been invented or designed that an independent or "second" look cannot improve upon.

The objective being the best design effectiveness in relation to long-term cost, particularly as reliability and maintainability affect it, we can hardly do less than apply the best available brains to review every tentative design. After such review the design engineer (or his supervisor) can decide exactly what recommendations to adopt, but not before. See chapter 15.

A few military specifications require that a military representative be invited to every review. There have been a number of occasions where the adoption of a recommended design improvement resulted in the military officially asking for some money back on the ground that the original design effort was improperly executed. Needless to say, this has the effect of inhibiting future improvement recommendations, or complete nullification of the benefit of design review. Perhaps some contractual protection of the contractor will solve the problem, as military participation is otherwise very beneficial. MIL STD 785 states:

> "3.5.6.1 Periodic design reviews for reliability (and maintainability) and evaluation of designs shall be conducted as an integral part of the contractor's engineering design review and evaluation procedures. These reviews shall evaluate the achievement of reliability (and maintainability) relative to the reliability (and maintainability) goals established for each major phase and review point of the contract; with contractor evaluation before designs are finalized. The reliability and maintainability design review analyses shall include, to the extent applicable:

Note that design review for reliability and/or maintainability separate from other design review is not desirable, as it would introduce unnecessary cost and delay. MIL STD 785 paragraph 3.5.6.1 goes on to say:

> (1) Reliability (and maintainability) estimates based upon prediction (785 suggests MIL STD 756 and MIL HDBK 217, but NAVSHIPS 93820 applies to BuShips) and accumulated test data. Estimates shall be made for each mode of operation.
>
> (2) Review of potential design or production problem areas.
>
> (3) Analysis of effects of failure.
>
> (4) Identification of the principal, critical items inhibiting reliability (and maintainability) achievement.

(5) The effects of engineering decisions and tradeoffs upon reliability (and maintainability) achievements, potential and growth.

The program plan shall specify appropriate personnel from the contractor's reliability (and maintainability) organizations who shall participate in the design reviews and denote approval by signature. These reviews shall be continuing in nature to provide for the earliest possible detection and correction of any potential deficiencies. A system shall be established and maintained by the contractor to assure reliability (and maintainability) participation in control of designs, specifications, drawings, and all changes thereto.

The design review shall compare the design with previously defined qualitative and quantitative requirements. The results of the review shall be documented.

The Procuring activity shall be notified at least 10 days prior to each scheduled formal design review (as distinguished from continuing), to permit procuring activity participation. The minutes of such reviews shall be made available to the procuring activity upon request."

Experience has shown that design reviews literally complying with the above may still be quite ineffective. There must be a clear policy on just what designs will be reviewed, to what depth, when, and by whom. Thus for more specific instruction in terms of the contractors task, these words have been found effective:

"The contractor shall conduct design reviews of all new designs and design changes, as well as any other designs whose reliability or maintainability are either unknown or suspect, including review of all interfaces and the effect of environment surrounding each subsystem, component, and part."

"He shall conduct such reviews at least of (a) complete conceptual design of systems and subsystems, prior to hardware component selection and detailed design, and of (b) complete hardware design prior to release for procurement and manufacture. However they should be planned for whatever design level or grouping of components will most economically provide adequate review of each new design and new interfaces only once.

"All design reviews shall be scheduled to follow appropriate design completions, allowing scheduled time and budget for design changes resulting from the review. Review participants time must be budgeted, but the cost is normally more than offset by retrofit cost savings. The cost can be minimized through use of standard checklists during design, which are then reviewed by the specialists prior to and during review."

"Every design review shall specifically consider quantitative reliability and maintainability relative to established requirements, as well as acquisition and ownership costs. Any deficiency from requirements, as well as all recommended design changes, shall be carried as Corrective Action Control items (see 13.0) until the deficiency or recommendation is resolved."

"Design review participation shall be limited to small groups including the responsible design engineer and appropriate specialists from other than the responsible design group, specifically including the chairman and at least one reliability/maintainability specialist."

11. PARTS CONTROL

Many contractors have excellent parts control procedures, but many do not. The basic problem is to prevent the selection of parts about which there is inadequate knowledge. It is particularly serious in the electronics or mechanisms areas, where the green young engineer can become sold on an elegant new part in the vendors catalog. It is "just what he needs" but has no history, no pedigree, no MTBF rating. See chapter 18. MIL STD 785 states:

"3.5.3 Parts Reliability. Parts shall not be used without knowledge of their capabilities and reliability potential determined from current or previous testing. Information shall be sought or generated on stress levels and limits of application as well as on failure rate. Available data and central information facilities shall be utilized to avoid needless duplication of testing. In using existing data, the risk and limitations of extrapolating part performance data at one set of environments to that expected at a different set of environments shall be recognized and documented. The best available estimate or determination of failure rate for each part type shall be made; the part vendor's accumulated test history under part specifications requiring failure rate verification shall be sought. Reported measure of achieved reliability should not be based upon short duration tests which predominately measure performance. If time does not permit adequate testing at advanced ages, the contractor shall show the age range actually tested and shall justify use of such data."

(3.5.3.1) "A preferred parts list shall be maintained and utilized as a source of high reliability parts."

In terms of the contractors tasks the following detail may be added if necessary:

"The program plan shall provide for a Parts Control activity responsible for (a) selection and cataloging of preferred parts that must be used by design engineers in preference to all other parts wherever feasible, (b) approval, or securing BuShips approval, of the use of each non-standard part in each application, (c) review of all parts application in Design Review, (d) consultation to design engineers on parts reliability and maintainability, availability and selection, (e) collection and dissemination of parts data needed by design engineers, including failure rate and cost, (f) writing all parts specifications to vendors, using military standard format where feasible, (g) controlling engineering stockroom content to minimize non-standard parts, (h) providing parts handling policy and procedure, and (i) providing traceability policy and procedure, so that failed parts may be traced by serial or lot number to eliminate their doubtful brothers."

12. REPORTS & PROJECT REVIEW

Most contracts generate volumes of reports that never get read, or at least by the people who can understand the significance and take action. The information they contain may be important, but is not in a form that a busy man can take time to read, and the distribution (because of report size and cost) may be inadequate. And while BuShips needs regular reports from the contractor to control the program, the contractors internal distribution of significant reports has far more impact on efficient and timely action. MIL STD 785 states:

"3.4 Program Review. The reliability (and maintainability) program shall be organized and scheduled to permit the contractor and the procuring activity to review its status, including results achieved, at preplanned steps or check points. This formal review and assessment of reliability (and maintainbility) normally will be conducted at major program points and these points will be established by the procuring activity during negotiations. As the program develops, reliability (and maintainability) progress shall be assessed by use of such information as predictions of reliability (and maintainability) and results of reliability (and maintainability) design reviews and tests including effects of human performance.

More specifically, the specification may state the specific information needed for the OPNAV 3910.15 reports, as well as for contractor internal control:

"The contractor shall conduct a summary reporting system which provides to each engineering supervisor a monthly one-page updated prediction of the availability (%), reliability (failure rate) and/or maintainability (MTTR) of each design for which he is responsible, with apportioned values shown beside each figure, flagging adverse discrepancies. It shall show the prior month and quarterly values to indicate trend. The contractor shall combine the above reports for higher-level one-page monthly reports of subsystem and overall system availability, reliability, and/or maintainability, for contractor management and for regular reporting to BuShips."

"The contractor shall provide a monthly report of audited task progress via (a) a status-vs.-plan copy of the task Schedule shown in Chapter 23, and (b) a report on each Task of the Program Plan, of not more than one page per task, for BuShips and contractor management, with copies of each page to contractor supervision who should take any needed corrective action."

If the contractor plans to conduct a running cost-effectiveness evaluation, Figure 22-19 shows a compact type of such report.

"If available, the contractor shall similarly show the cost-effectiveness trend quarterly."

13. CORRECTIVE ACTION CONTROL

Human nature being what it is, many recognized problems never get fixed because they are forgotten in the pressure of bigger problems. A very effective solution to this problem is a fairly automatic problem logging system, with a named individual responsible to fix each problem. When such "needle" logs are regularly issued, audit of progress is simple, and most people want to get

MONTHLY COST-EFFECTIVENESS REPORT

SYSTEM and CONTRACTOR	COST EFFEC-TIVENESS	EFFECTIVENESS					TOTAL COST in $millions			
		Perfor Capab.	Avail-abili.	Deliv. Effec.	Utili-zation	NET (PADU)	Acquisition Basic	Acquisition R&M	Owner-ship	TOTAL (sum)
	E/C	P%	A%	D%	U%	E%	C_a	C_r	C_o	C
POLAR K by "A"										
Required (est.)	(.95)	100	70	100	(95)	(66)	(20)	(2)	(48)	(70)
Predicted Now	1.31	100*	80*	95	95	72	20	3.0*	32	55
Last report	1.02	105	75	95	95	71	20	1.3	48	69
Actual Recent	.56	95	60	100	90	51	18	1.7	72	92
Cumulative	.22	90	50	90	70	28	18	0.3	108	126
POLAR K by "B"										
Required										
Predicted Now	1.78	95	90	90	95	73	19	6	16	41
Last report										
Actual Recent										
Cumulative										

*Design change authorized to obtain higher cost-effectiveness via reliability, at increased Acquisition Cost and some sacrifice of performance.

off the hook. MIL STD 785 states:

> (3.3.3) "Records shall be maintained on the status of actions to resolve problems."

Since the above words require no more than paperwork recording what happened, as opposed to methods for assuring action, the Project Engineer may wish to pin it down further:

> "The contractor shall conduct a Corrective Action Control System wherein (a) every predicted failure to achieve required reliability and maintainability, (b) every unresolved design review recommendation, and (c) every production and operational hardware failure is logged and remains as an 'action required' item until resolved to the satisfaction of the reliability and maintainability group(s). Each item will show the name of one individual directly responsible for resolution, and the date by which resolution is planned. In the case of production hardware failures, resolution must include steps to prevent the same failure again in that or other hardware."

14. CHANGE AND CONFIGURATION CONTROL

The problem of keeping track of detailed changes, their interfaces, and their impact on logistics for a complex system is a big task, It goes far beyond reliability and maintainability considerations, yet has quite an impact thereon. See chapter 21. Unless control procedures are established, change control groups often make decisions without realizing the consequences:

> "The contractor shall provide control procedures whereby design and configuration changes cannot be approved without quantitative consideration of resultant reliability and maintainability of the design and its interfaces, in the local environment. The procedures must insure that such changes are immediately incorporated into the prediction model."

15. SUPPLIER CONTROL

Since subcontractors and vendors normally provide the bulk of the hardware, and often substantial portions of the design, it is imperative that all provisions of the Program Plan be executed by all suppliers to an appropriate depth. See chapter 19. This appropriate depth is sometimes difficult to determine, and the contractor can only ask himself, "If I were designing and manufacturing this component, knowing what I do about my application of it, what tasks would I undertake to make very sure of getting the required reliability and maintainability?"

There is also the problem of the excellent supplier who says in effect, "I know my product is good, and I don't need your business so much that I want to bother with this reliability legerdemain." If he is the only source, it's a tough nut. But some contractors are pretty resourceful. MIL STD 785 states:

> "3.5.7 Supplier and Subcontractor Reliability (and Maintainability) Programs. The contractor shall be responsible for assuring that supplier's and subcontractors' achieved reliability (and maintainability) levels are consistent with overall system requirements. The contractor shall impose, directly or indirectly, quantitative reliability (and maintainability) requirements and acceptance criteria on all echelons of suppliers and subcontractors; and shall incorporate applicable portions of this standard in subcontracts and purchase orders. The reliability (and maintainability) program of the contractor shall contain provisions for surveillance of supplier and subcontractor reliability (and maintainability) activities including failure reporting. The surveillance shall consist of but not limited to such items as maintaining a supplier selection program based upon review of the supplier's reliability (and maintainability) program, quality control system, examination of his facilities, and past performance, to assure that suppliers are capable of attaining and maintaining the required level of reliability (and maintainability). The contractor shall take all actions necessary to assure that no changes made by any supplier will reduce reliability (or maintainability) of the system. Records of each supplier's performance shall be maintained and reviewed with him periodically."

In terms of the contractors task, a comprehensive program would be established with these words:

> "The contractor shall conduct a survey of the reliability and maintainability capability of each finally-considered supplier to evaluate (a) his design engineering knowledge of reliability and maintainability requirements, (b) the means to achieve such requirements, (c) the analysis techniques, (d) his management understanding and support of the tasks required, and (e) existing conduct of such tasks. The survey shall consider the above reliability and maintainability cap-

ability, as well as quantitative evidence of achieved MTBF and MTTR, as prime factors in the selection of every supplier."

"For every suppliers component whose criticality (effect on system reliability) exceeds a predetermined level, the contractor shall include in the specification to the supplier the required quantitative reliability and maintainability, and the test or other criteria by which they will be verified prior to shipment. Specifications detailing all technical requirements, including tolerances, shall be used for all critical components whose failure would cause system failure· ordering by vendor catalog number alone is prohibited."

"The contractor shall require reliability and maintainability test data, and monthly predictions of product reliability and maintainability from each supplier of a component whose applied criticality exceeds the predetermined level, whether in design or production. He shall require monthly progress reports of each such suppliers Program Plan task, and take appropriate action."

"The contractor shall conduct re-surveys every 6 to 12 months, identical to the pre-award survey and evaluation. He will maintain for each supplier a current rating of reliability and maintainability (a) engineering capability, (b) task performance, and (c) actual quantitative achievement vs. prediction, for use in future source selections."

16. MANUFACTURING R & M CONTROL

Once a design is released to manufacture, it has an inherent reliability that will either be achieved through good Quality Control, or degraded through lack of it. See chapter 20. While Quality Control is outside the scope of this course, there are a few tasks that otherwise might not be part of the QC program. Here MIL STD 785 refers to "Critical Items" by which is meant "items whose failure would cause system failure." In many systems this can be 80% of the hardware, so that the "special handling" aspect becomes meaningless, and such requirements are thus sometimes waived. MIL STD 785 states:

"3.5.4 Critical Items. The contractor shall establish an effective method for identification, control and special handling of critical parts, components, subsystems or other end items from design through final acceptance. Such methods shall be described in the contractor's formal policies and procedures to assure awareness by all affected personnel (e.g. design, purchasing, manufacturing, inspection, test, handling, etc.) of the essential and critical nature of such items. The methodology used in generating the critical item list shall be furnished to the procuring activity. The method used and the list subsequently generated shall be subject to review and evaluation of the procuring activity."

"3.5.14 Manufacturing Controls and Monitoring. The contractor shall have a planned, controlled and scheduled system of production control and monitoring to assure that reliability (and maintainability) achieved in design is maintained during production."

When reliability models are used, every component can be assigned a "criticality" number, the simplest form of which is merely the system failure rate increment due to all of that particular component, considering its own failure rate and the way it is used. Thus the above "critical item" control is better handled as control of items having a criticality above a predetermined value. Other aspects, in terms of the contractors detailed tasks, may be worded:

"The contractor shall plan, control, and audit the procurement, manufacturing, test and transportation program so that (a) only known-reliability and traceable parts and components can be used (b) parts and components are packaged and handled in a manner that does not degrade reliability by shock, wear, etc., (c) each component carries with it a log of the serial or lot numbers of its constituents, and (d) a log of every test showing the operational time duration, stress, environment, failure time and descriptions, and the downtime actions taken, with time for each, (e) no overstress is applied to deliverable items, and (f) storage, shelf-life, and transportation do not degrade reliability."

17. FAILURE DIAGNOSIS

Failure in design evaluation, manufacture, test, or operational use may or may not be due to faulty parts, since a technician may have adjusted something improperly, or let his screwdriver fall into a sensitive circuit. And usually he won't admit it. Also operators have been known to make mistakes, reporting a failure to protect their hides. But without human error, and without faulty parts, components can still fail to work due to design tolerances or interfaces between parts. See chapter 16.

But if reliability is important, there must be one ironclad rule about all failures. Never, but never, should a failure go undiagnosed, nor unrecorded. Fix the failure, yes, but it is far more important to take meticulous steps to prevent its recurrence. MIL STD 785 states:

"3.5.3.2 Emergency Reporting of Defective Parts. When a MIL specification or a MIL part is deemed suspect by the development contractor, the contractor shall: (a) indicate reason with supporting evidence of this conclusion, (b) perform failed part diagnosis and analysis of those parts deemed suspect development, acceptance tests, and other related activities, (c) whenever possible, reach a conclusion relative to the cause of failure, and (d) report by most expeditious means to the procuring activity with concise supporting data when, and only when, it has been concluded that a part is unsatisfactory for any of the following reasons:

(1) A part which was accepted as meeting a MIL specification but which failed to perform to expectations, such failure concluded to be (attributable to: (a) manufacturing procedures, choice of material, or design of part, or (b) test and inspection disciplines.

(2) A military part specification which is inadequate in that it (a) does not take advantage of the state-of-the-art, (b) requires amendment to encourage advancement of the state-of-the-art, or (c) requires revision for clarity."

"3.5.15 Failure Data Collection, Analysis, and Corrective Action. (a) The contractor shall have and shall require major subcontractors to have a closed-loop system for collecting, analyzing, and recording all failures that occur during phases of tests required for system elements including those that are performed in-plant and at installation sites. The contractor shall describe his failure reporting procedures, including flow charts, for the analysis, feedback and corrective action as part of the program plan (see 3.3.5). The failure reporting system shall include provisions to assure that effective corrective actions are taken on a timely basis to reduce or prevent repetition of the failures. The contractor shall establish scheduled audits to review all open reports, analyses, dates for corrective action and report all delinquencies to management."

"(b) The contractor shall commence failure reporting with initial development testing or operation including operating equipment at receiving inspection, at a vendor's plant in final assembly checkout, or during acceptance testing. An unscheduled adjustment, other than a calibration made during other maintenance because of convenience, shall be defined as a failure for reporting purposes. Failure of components prior to incorporation into an assembly shall be recorded separately and reported."

"(c) The contractor shall submit failure report summaries as specified by the procuring activity."

18. DATA ACQUISITION & REDUCTION

Without convincing evidence that his beloved brain-child is unreliable, the design engineer cannot take seriously the claim that higher reliability is needed. That evidence is operational stress time and failure data. The source of such data can only be the user of the system, in this case the Navy. A real solution to the problem is not yet in sight, though several groups are working hard on it. See Chapter 9.

One problem is that the maintenance technician himself is never a dependable data collector. He often has tremendous pressure to restore operation, ignoring data needs until a time that it can no longer be obtained. One survey (8 p.217 No.10) states that only 10 to 20% of Navy failures are getting reported. See Chapter 26, Sections 8.10-8.12.

Another problem is that overlapping needs for data will result in excessive maintenance site paperwork unless they are consolidated into a simple format. Another is that even when data gets back to a contractor, often he is not funded to analyze it properly it properly for BuShips or even his own future guidance. Mil-Std-785 states:

(3.5.15) "The contractor shall explain the method by which failure reports are initiated. Analysis and recording of failures shall differentiate between, but not be restricted to, those due to equipment failure and those due to human error in designing, processing, handling, transporting, storing, maintaining, and operating the equipment. Elapsed time indicators or event counters shall be utilized or a log shall be maintained to report accumulated operation time or operation cycles on system components that are time or operation-cycle sensitive. The failure reporting system shall be designed to be compatible with the maintenance data collection system of the procuring or using activity so that, as the system nears the operational inventory phase, transition to in-service failure reporting can be accomplished with the minimum disturbance and maximum continuity of effort."

Long before the contractor has any hardware to fail, his design engineers need the best obtainable data in order to achieve the required reliability and maintainability. Then as the hardware is produced he needs it to evaluate test results, and then operational data permits refinement of that and future designs. BuShips can get better designs if it is in a position to offer:

"BuShips will provide pertinent obtainable operational reliability (stress time and failures), maintainability (MTTR), manhours/failure and cost ($ per failure other than manhours) data to the contractor. During design, manufacture, test and checkout, it will be on components similar to those to be furnished to the contractor. During operational use it will be on the system, subsystems, and components furnished by the contractor, furnished periodically until the system is retired."

Another problem is that only a few contractors have developed continuously-operating data-reduction systems that provide information to design engineers in convenient form. See chapter 18 section 4.1 for such a system now under development.

"The contractor shall collect corresponding data from his own design, suppliers, production, test, and checkout activity. He shall combine this with data furnished by BuShips to maintain current records of reliability, maintainability and total cost of all components, with due regard to environments involved. This shall be made available for convenient use by all design engineers on current and subsequent system designs."

"He shall analyze such data and, using his reliability and/or availability model of the system, quarterly report the current system and subsystem reliability and availability and (if available) cost-effectiveness to the Bureau."

19. VERIFICATION

Seldom can we wait until an entire system is assembled to find out by test whether it has adequate reliability and maintainability. For by then the accumulation of errors would almost certainly guarantee serious schedule slippage and cost overrun. On the other hand we cannot afford a separate sequential test for every unknown or unverified parameter. Thus most contractors develop "integrated test" plans which seek to get the maximum information out of the fewest possible number of tests, and at the earliest feasible time to permit scheduled correction of deficiencies. Mil-Std-785 states:

"3.5.1 Test Requirements for Development Qualification and Acceptance. A Planned and scheduled program of functional and environmental testing of equipment shall be conducted during design and development phases to estimate achieved reliability and to provide feedback of data as a basis for making reliability improvements. The development testing program shall confirm adequacy of selection of components and parts, determine capabilities and safety margins, evaluate drifts of component parameters with time, and determine failure-modes and relative failure-rates."

"If such data are not available, all items of the system determined by the reliability studies (3.3.2 and 3.3.3) to have a significant bearing on inherent reliability shall be tested early in the development program, unless other valid proof of adequacy can be presented."

Keeping in mind the discussion of "critical item" vs. "criticality" in Section 16.0 above, Mil-Std.-785 states:

"3.5.1.1 Environmental Requirements for Equipment Design and Testing. If maximum environmental stress conditions have not been established by the producing activity these shall be estimated from experience on past programs, and a test program for development, qualification, and acceptance shall be generated on this basis. Development and qualification tests shall be planned to evaluate the adequacy of design of equipment for the expected conditions in the use-environment (e.g., ground operation, launch, flight and orbit). The test plans shall include consideration of equipment, location, insulation shock-mounting, truss mounting, etc."

"Environmental problem areas shall be identified at the system, subsystem, component and part level, and the effects of these problems on system reliability shall be estimated on equipments, components, or parts identified as critical. Detailed and specific review of environmental factors affecting reliability shall be performed. In addition to qualification and acceptance testing, additional testing shall be performed on critical items, such as life testing or failure-mode testing, to assess the affects of the environments on such critical items, and to determine adequacy of safety margins incorporated by system design, subject to approval by the procuring activity."

"3.5.1.2 Component Part Testing. All component parts to be used in production equipment shall be assigned a reliability index, failure rate, or expected probability of failure under stated stress levels. The reliability test procedures of applicable military part specifications and testing specifications shall be used. Where the contractor deems these test procedures not applicable, he shall submit a justification of non-applicability and a description of the test procedures which he plans to use. A current record of the results shall be maintained. The test data shall be retained for a minimum period of two years from completion of contract. The test data shall be made available to information and data exchange activities upon request of the procuring activity."

"3.5.1.3 Maximum Preacceptance Operation. The contractor shall provide and maintain a current list of items having critically limited useful lives (total operating time or operating cycle) in their application. Derivation of maximum allowable operating time (or cycles of operation) shall be clearly defined with elements of data and methods of computations. The contractor shall propose for approval the time or number of equivalent operating cycles that is not to be exceeded prior to acceptance of the contractor's product. He shall ensure that each such item has its total operating time or number of equivalent operating cycles recorded, starting with and including its initial functional test, whether at the contractor's facility or a supplier's facility. Upon mutual agreement between the procuring activity and the contractor, any item may be dropped from the above list, or its limit revised, when changes in the items useful life indicate the need for such revisions."

"3.5.10 Statistical Methods. The contractor's reliability program shall incorporate optimum utilization of statistical planning and analysis. This shall include application of such methods as design of experiment, analysis of variance, and other methods applicable to design, development and production phases."

The basic final verification of achieved reliability is the "sequential" life test, which is usually what is meant by "reliability demonstrations". However the following Mil-Std-785 paragraphs do not limit reliability testing to such sequential life tests:

"3.5.16 Reliability Demonstration

"3.5.16.1 Initial Plan. An initial plan for demonstration of achieved reliability (and maintainability) at specified milestones, including estimated number of test articles and if not specified by the procuring activity a quantitative estimate of the confidence level, shall be prepared by the contractor and submitted in a section of the reliability program plan. The general plans for demonstration of reliability shall include trade-off curves showing number of test articles and operating test time or test effort versus confidence, and will encompass testing at the system major element level, and major subsystem or component levels separately and in combination."

"3.5.16.2 Final Plan. Final plan for demonstrating achieved reliability (and maintainability) shall include any revisions to data in the initial plan, and the ground rules and conditions for deciding whether a test shall be classified as a success or failure, or shall be excluded due to invalid test data. Reliability demonstration plans shall apply all results of testing and operations from which valid reliability measurement or assessment can be obtained. Engineering tests and analysis, e.g., test to failure concepts, shall be included to supplement statistical measures. The milestones that are to constitute demonstration of contract compliance shall be established and incorporated in the contractual documents. Specific plans for conducting a reliability demonstration shall be submitted for approval at the time specified by the procuring activity."

"3.5.16.3 Test Plans. The test plans contained in (785 says Mil-Std-781, but BuShips test plans are contained in Mil-R-22732B), when applicable, shall be applied."

But often reliability life tests are utterly impractical time- and cost-wise, so verification has to be achieved by other means. See Chapter 11. Since testing is often the most expensive part of a reliability program, this section of the Program Plan deserves considerable emphasis. There should be provision for the other techniques where they are necessary. And simple economy demands some kind of integrated test plan:

"The contractor shall completely list and briefly describe the parts, components, and system to undergo any kind of verification of reliability or maintainability. Most of these will be part of a larger list of all components to be tested, included in the Technical Proposal, and should be coded thereto."

"For each component above to be tested, he will refer to a description of the applicable reliability and/or maintainability test procedure, and state quantity to be tested, test criteria, and results anticipated."

"For each component above to be verified by other than test, he will briefly state the rationale for such decision, the anticipated analytical procedure, criteria, and results anticipated."

"The contractor will provide a chart showing the time, in relation to overall design, manufacture, and acceptance test schedules, at which each above test or other verification will be conducted."

20. SUMMARY

In this chapter we have described, in words that may be used by the Project Engineer to the contractor, 19 quite basic reliability and maintainability tasks. A comprehensive program on a large project will require the contractor to do nearly all of them. A small project, or a parts supplier, may need to do only a few of them. The determination of such selection and depth is covered in Chapter 23.

Mil-Std-785 is quoted verbatim herein wherever applicable to the 19 tasks, and all its remaining paragraphs, since they do not apply to specific tasks, are quoted in Chapter 23. It will be apparent that Mil-Std-785 must be supplemented by additional tasks and detail wherever a comprehensive program is needed

21. REFERENCES

(1) Reliability Management of Department of Defense Military Systems, Military Standard Mil-Std-785.

(2) Reliability Requirements for Shipboard and Ground Electronic Equipment, Military Specification Mil-R-22732B (SHIPS), Amendment 1, 10 March 1964.

(3) Maintainability Requirements for Shipboard and Shore Electronic Equipment and Systems, Military Specification Mil-M-23313A (SHIPS), Amendment 1, 29 January 1964.

(4) Industrial Universities, Time Magazine, August 28, 1964,

page 44.

(5) <u>Presentation for AIAA-SAE-ASME Reliability and Maintainability Conference</u>, by Rear Admiral Emerson Fawkes, USN, Assistant Chief, BuWeps R&D Test & Evaluation, May 7, 1963.

(6) <u>Value Engineering Handbook H111</u>, 26 March 1963, Office of the Assistant Secretary of Defense (Installations and Logistics), Washington 25, D. C.

(7) <u>Value Engineering of Naval Ordnance Equipment, Mil-V-21237</u>. Also <u>BuWeps Note 13052</u> dated September 1961. Also <u>Value Engineering of Naval Electronic Equipment, Mil-V-19858.</u> Also <u>Navy Specification and Requirements Improvement Program 4120,14</u> dated 1 May 1962.

(8) <u>Design of Equipment to Optimize Reliability for Manufacturers and Customers Minimum Total Cost</u>, by Dr. D. Kececioglu and R. C. Hughes, February 1963, Proceedings of Conference on Advanced Marine Engineering Concepts for Increased Reliability, The University of Michigan, Ann Arbor, Michigan. Contract NONR-3931(00) (FBM).

Chapter 23

CONTRACT PLANNING

Chapter 23

CONTRACT PLANNING

This chapter deals with the broad content of reliability and maintainability programs, with emphasis upon the Project Management actions necessary to plan and organize such programs to match the requirements. The Project Management actions necessary to conduct, evaluate and control such programs will be found in Chapter 24. Detailed treatment of specific program elements will be found in Chapters 3 through 22.

Throughout this chapter and Chapter 22, the MIL-STD-785 specification language is quoted wherever it is applicable, and supplemented by other language as needed. Thus these two chapters contain all such selected and recommended specification language. However, Chapter 17 contains extracts from many other specifications, useful as a reference for special situations.

1. REQUIREMENT ESTABLISHMENT

DOD has issued (1) Directive 3200.9 requiring a Project Definition Phase I preceding Acquisition Phase II (for actual hardware development and production) applicable to all new (or major modification) RDT&E Engineering Development or Operational System Development projects over $25 million, or requiring production costing over $100 million. PDP Phase I results in a PDP Report which actually contains the requirements for Phase II. Whether or not PDP is applicable to a given BuShips program, the requirements (2) listed in Figure 23-4 express the DOD point of view, and can serve as a policy for any program.

The purpose of any reliability and maintainability program is to actually achieve the optimum quantitative level of reliability and maintainability. To achieve less produces inadequate system effectiveness and/or excessive maintenance cost. To achieve more may require excessive contractor program costs. Thus it is obvious that solid requirements must be established before it is possible to determine an appropriate program. The detailed steps for definition of requirements have been given in Chapter 2.

1.1 ENVIRONMENT AND STRESS

The BuShips Technical Code should first thoroughly establish the conditions, in as much detail as feasible, under which the planned system must operate for all probable missions during its use-

DOD on REQUIREMENTS

Directive 3200.9

Project Definition Phase Reports

VE6

PDP Reports and Proposals. Each participant shall submit a report containing a complete technical, management, and cost proposal for the Phase II development. The report will include the information outlined in Inclosure (2):

Inclosure (2)

5. Principal objectives and features of the over-all system design, including recommendations for its operational use based on operational concepts established by the Department or Agency.

6. A recommended plan for maintenance of the system based upon maintenance and logistic concepts established by the Department or Agency.

7. Detailed cost estimates for Phase II, which include cost estimates for the items of the work breakdown structure, as derived from PERT/Cost; together with planning estimates for the period beyond Phase II (investment and operating cost for five years, including production, operation, maintenance, etc.).

9. Quantitative reliability and maintainability specifications for the system and major subsystems and proposed test plans to demonstrate their achievement.

10. Time-cost performance trade-off decisions which have been made with respect to major alternatives, including subsystems and components, and back-up information showing the operational and cost-effectiveness of these alternatives.

19. Contractor proposals on the specific features of an incentive contract. (This arrangement is considered important because it will permit the negotiation of targets and incentive patterns into the contract while competivite proposals are still available and furnish the basis for incentive provisions in the contract.)

Signed by Robert S. McNamara

ful lifetime. The Project Engineer should:

"Completely state the operational environment and external stresses acting on the system, by mission and operational phase or mode, for the anticipated system lifetime, using stress distributions whenever feasible.

1.2 COST-EFFECTIVENESS ANALYSIS

See Section 5.1 for future provisions.

1.3 QUANTITATIVE DESIGN REQUIREMENTS

Satisfaction of these requirements is the basic objective of the entire Reliability and Maintainability Program Plan. The Project Engineer should therefore:

"State the required minimum acceptable (mandatory) and optimum reliability (MTBF, % success for specified mission time, etc.), maintainability (MTTR, MAXTR, manpower, etc.) and/or availability (% uptime on demand, continuously, etc., together with the test acceptance criteria or other means by which each will be verified prior to BuShips acceptance, and wherever feasible, the quantitative required confidence levels."

1.4 APPLICABLE DOCUMENTS

Several documents are always applicable by DOD, Navy, and BuShips policy. However most of these are quite broad, so that some individual sections of them do not logically apply. Thus it is very important, in the interest of economy and to avoid the propagation of unnecessary paperwork and confusion, to select the applicable sections. The Project Engineer should therefore:

"Based on the actual reliability and maintainability values to be required of the contractor, and taking all BuShips policies into account, list the applicable top documents. For each document specifically list the section numbers that apply, together with any modification of a section language that may be necessary. Identify which are mandatory and which subject to contractor recommendation. Provide a file record of the reasons for the above."

2. PROPOSAL MANAGEMENT

So far as reliability and maintainability are concerned, this may be the most critical phase, deserving the greatest attention.

For it is a fact that there are far more "lip service" reliability programs, even among otherwise very competent contractors, than there are bona fide reliability achievement programs. Every possible step must be taken to make sure the potential contractor understands what he is getting into.

2.1 REQUEST FOR PROPOSAL

Again let's review in Figures 23-7 and 23-8 what the DOD viewpoint is for R&D over $25 million. We continue to find heavy emphasis upon definition of requirements, encouragement of contractor alternative recommendations, and the balance of cost, schedule and performance (i.e., effectiveness). We find instruction to advise the contractor concerning proposal evaluation criteria and the requirement for specification of quantitative reliability and maintainability.

We will concern ourselves only with those elements of a Request for Proposal (RFP) or Procurement Request that affect reliability and maintainability, since all other elements are thoroughly covered elsewhere. In each of the following sections we will give a bit of background, followed by paragraphs (in quotes) as examples of wording that BuShips engineers may use in writing the RFP.

2.1.1 Requirements: As a result of the prior definition and analysis work outlined in Sections 1.1, 1.3 and 1.4 above, the Project Engineer is in a position to state requirements in the RFP. Should he temporarily be unable to specify reliability and maintainability requirements, the contractor should nevertheless be asked to state what he will achieve.

2.1.2 Cost-Effectiveness Analysis: See Section 5.1.1 for future provisions.

2.1.3 Program Plan: This principal element of the RFP, Proposal and resultant contract is treated separately in section 3. and its detailed Task Delination in chapter 22.

2.1.4 Proposal Due Dates: It is an unfortunate fact that many proposals are assembled in a great deal of pressure, without adequate time for analysis, supplier consultation, and thorough costing. What is worse, the reliability and maintainbbility specialists are often asked to "write a page or two," with no opportunity for influencing the proposed design and its costing. The reasons are largely in the contractors own house, and the suggested RFP wording in this chapter should get attention by

DOD on REQUESTS FOR PROPOSALS

Directive 3200.9

Participation
VE1a

Normally, in-house laboratories can contribute most effectively to the research-to-production cycle in the exploratory and advanced development prior to PDP and as technical directors for the PDP and Phase II rather than by conducting PDP or Phase II. It is recognized that exceptions to this rule may be necessary; where necessary, such exceptions will be authorized on a case-by-case basis.

A genuinely competitive environment shall be established, with the competition in terms of concept, design approach, trade-off solutions, management plans, schedule and similar factors as well as overall cost.

Contractor Project Definition Phase
VE2

The RFP must communicate fully the Government's intent and, based upon Government definition prior to release of the RFP, specify requirements fully and in detail, identifying those which are mandatory and those which are subject to deviation.

It is essential that the RFP encourage alternatives and stimulate initiative and creativity by the contractors.

The RFP shall include the information outlined in Inclosure (1), (Figure 23-8).

Phase II Proposals
VE6

Proposals for incentive contracts will include specific incentive features based upon guidance furnished by the Government in the RFP and subsequently. Incentive guidance typically will include the relative importance of cost, schedule, and performance; important milestones, and performance parameters upon which incentives will be based.

DOD on REQUESTS FOR PROPOSALS

INCLOSURE (1) of Directive 3200.9

It is essential that information be included in the Request for Proposal (RFP) on which potential contractors may base high quality proposals. Both technical and managerial aspects of the proposed development must be considered thoroughly in the RFP and the resultant proposals. The RFP shall include, but shall not be limited to, the following items (except as specifically exempted by the DDR&E):

1. System requirements based upon approved program guidance.

2. Results of prior studies (including feasibility, cost-effectiveness, major trade-offs, operational analysis, logistics analysis, etc.) deemed necessary for adequate background information for the contractors.

3. Criteria against which proposals will be evaluated, and their relative importance in general terms.

10. Incentive features desired in the Phase II proposal, including relative importance of incentives, and specific schedule and performance items that will be subject to incentives.

12. Quantitative reliability and maintainability goals and demonstration concepts.

14. Identification of specifications, with any waivers or deviations, planned to be written into the resulting Phase II contract.

15. Documentation requirements during the Phase II contract.

the right people.

Under no circumstances should the known desirable bidders be given less than 60 days after receipt of the RFP and attendance at the bidders conference. If a thorough analysis is required, such as the cost-effectiveness analysis in section 2.1.2, it should be 90 days. Another suggestion is to provide a series of due dates, requiring the analysis, design, and management/cost proposals sequentially 30 days apart.

2.2 BIDDER SELECTION AND CONFERENCE

Of course bidders are always selected from among those known to have the technical and management capability, particularly including those having experience with similar design and construction. The following is quoted (5) from DOD Defense Procurement Circular dated 4 March 1964:

> "In working toward better defense procurement, nothing is more basic to satisfactory procurement than that we deal only with responsible prospective contractors. Contract awards to concerns of marginal capabilities can lead only to delays or failures in obtaining delivery of needed items and to increased eventual costs to the Government."
>
> "The present regulatory guidance on responsible prospective contractors (ASPR Section I, Part 9) is adequate. It is not that new rules are needed, but that our present rules must be understood and followed. Importantly, ASPR requires an affirmative determination that the prospective contractor is responsible before any contract award may be made: there must be a positive judgment that he will perform the contract on schedule in accordance with its terms.
>
> This excludes the company whose qualifications are no better than borderline as to production capacity, financial capability, past performance, or any of the other minimum standards. It excludes the company whose continuing capability throughout the period of performance is jeopardized by a pending bankruptcy reorganization or other evidence of financial difficulty which may culminate in loss of needed financial capabilities during the period of contract performance.
>
> It means that, in predicting whether a company will perform the contract satisfactorily, it must be assumed that the Government will use vigilant and forceful contract administration. It is not acceptable to make a determination of res-

ponsibility which envisions completed contract performance only after extreme Government financial assistance and marked lenience in enforcing delivery schedules or other contract terms.

"Full understanding of the importance of affirmatively determining that the prospective contractor is responsible should assist our efforts to increase the use of formally advertised procurement. Use of negotiation is never justified by a fear that advertising may lead to award to a contractor who is unlikely to perform satisfactorily. The standards of responsibility for contractors are precisely the same for advertised as for negotiated procurements. If a company would be rejected as not responsible notwithstanding a low offer in a negotiated procurement, the same company should be rejected notwithstanding a low bid on an equivalent advertised procurement. The contracting officer has the same right and duty to determine nonresponsibility in one case as in the other.

"I have asked the Assistant Secretary of Defense (Installations and Logistics) to take the necessary steps to bring the importance of responsibility determinations to the attention of all contracting officers.

"Signed
ROBERT S. McNAMARA
Secretary of Defense"

The recent incorporation of quantitative reliability and maintainability requirements certainly does not change these very sound selection criteria. On the other hand these techniques, and the tasks necessary to achieve specified reliability and maintainability, are new to many BuShips contractors. Some will not know what "MTBF" means. They will have many questions, and there is no satisfactory substitute for a bidders conference at which the Bureau design and reliability/maintainability people jointly respond to the questions. But unless the contractors reliability/maintainability specialist is specifically invited, the contractor probably won't send one even when he does have such competence. The Project Engineer may write in the RFP:

"The contractor will send questions concerning reliability and maintainability, in writing, to (state name, address) to arrive no later than (state date). He will then send one reliability/maintainability specialist, as well as other invited representatives, to the bidders conference to be held (state date, time and place)."

2.3 PROPOSAL EVALUATION

Background, formats, and procedures for proposal evaluation are discussed in section 4.

2.4 CONTRACT NEGOTIATION

This is a large subject. We are concerned here only with those aspects related to reliability and maintainability. But these aspects are so serious that they have unquestionably caused much system unreliability.

2.4.1 Traditional Approach: Wherever the design techniques are well-established, and all contractors know very well just what they have to do to satisfy the stated needs, the traditional contractual approach works fine. BuShips states its exact requirements, the contractors bid, and award is made to the lowest bidder who has the necessary capability.

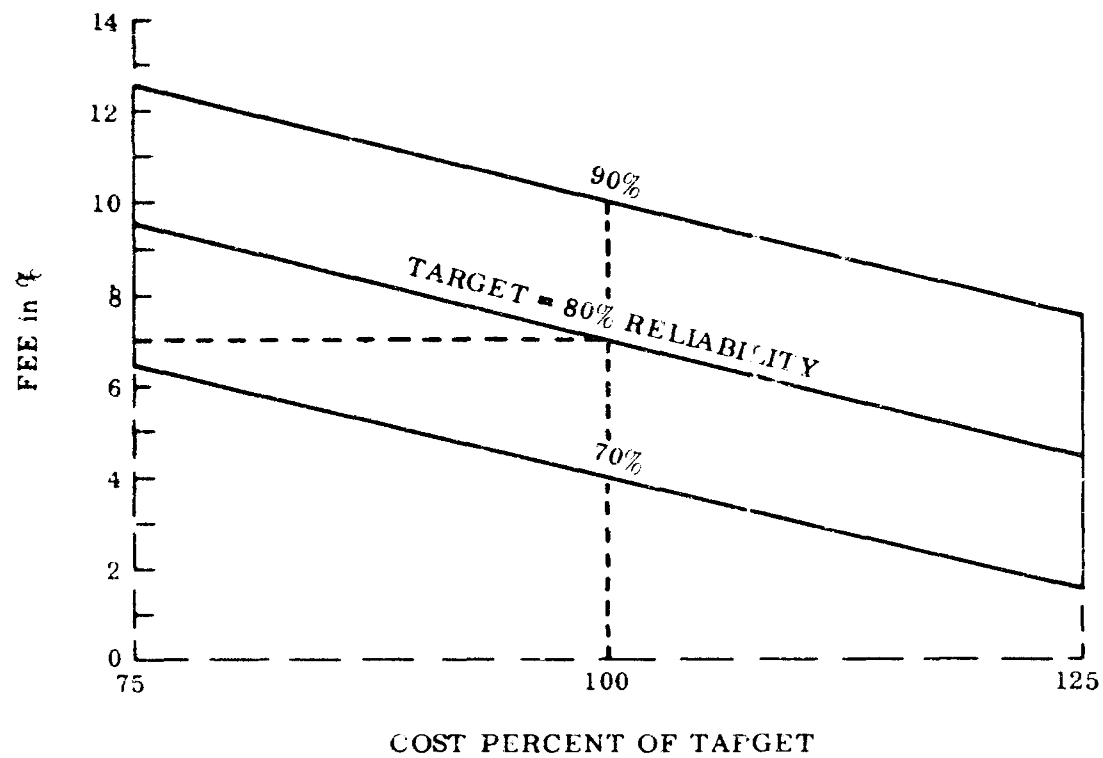
2.4.2 Advance Development Approach: When the design techniques are not yet established, and no capable contractor can be sure what development will cost, the cost-plus-fixed-fee approach has been widely used. However it has been abused and is currently discredited. But it does recognize the basic problem of contracting for uncertainty.

Now reliability, in its youth, reflects a design uncertainty. Not only that, it is an uncertainty of much greater impact on cost and effectiveness than many typical cost-plus development uncertainties. Small wonder that it is difficult to get realistic fixed price commitments on new developments with guaranteed reliability.

2.4.3 Reliability Incentive Contracts: Recent DOD instructions (6) for incentive contracting treat Reliability (barely) as part of "performance", (not Performance Capability), and Availability not at all. They do not reflect recognition of the problem that has arisen.

There have been a few contracts that adjust the percent fee in accordance with achieved values of % reliability. Typically such a contract has paid the order 0.3% added fee for each percent of reliability improvement above a stated target, and conversely below it. This is in addition to the cost-incentive fee that pays 10% of any savings below a target, and conversely above. Figure 23-12 shows how it works.

RELIABILITY & COST INCENTIVE



Unfortunately the cost to contractor of achieving say 2% higher reliability is <u>much greater at 90% than 70%</u>. The difficulty and cost depends directly upon how close the reliability is to 100%. So the more reliability a contractor achieves the less he is paid for it. It works out so that the contractor is actually penalized if he tries to get over 90%. See Chapter 26, section 7.8.

2.4.4 <u>Contracting for Cost-Effectiveness:</u> See section 5.1.2 for future provisions.

2.4.5 <u>Task Negotiation:</u> Every proposed task should be analyzed for content, output, who needs it, and manpower. "Who needs it" must account for Bureau as well as contractor needs. Figure 23-14 shows how reliability can be substantially affected by task selection, even without increasing Acquisition Cost, but that actual design for specified reliability requires additional design costs.

The ultimate determination whether each task is needed should be made only by the Project Engineer based on analysis by BuShips reliability/maintainability specialists. The ultimate decision concerning proper <u>manpower</u> for each task should be made only by the contractors reliability/maintainability representative. Negotiation will often be detrimental to reliability and cost-effectiveness unless both are present. See Chapter 24, section 4. The reliability of many systems has been <u>degraded</u> by negotiation decisions made by people unaware of the consequences.

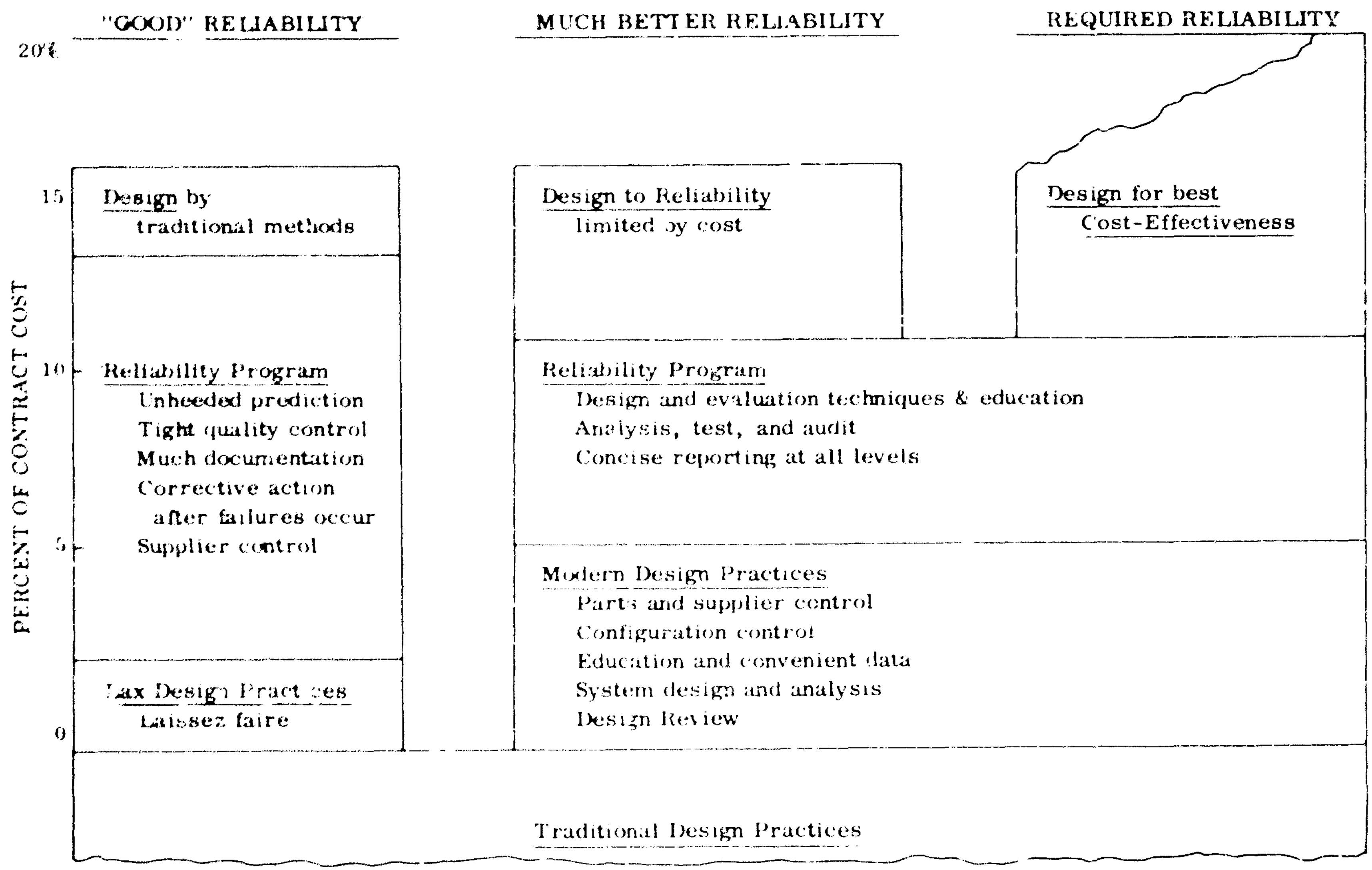
<u>2.5 CHANGE PROPOSALS</u>

Change proposals, either by the contractor or BuShips, should be evaluated identically to new proposals. It makes little sense to carefully evaluate the original proposal and make decisions vitally affecting reliability, then ignore the effect of altered reliability and maintainability in changes.

On the other hand, it is very demoralizing for a contractor to propose change after change that his reliability prediction says are needed to achieve required reliability, only to have them turned down by the customer for reasons like "logistic problems". This keeps happening.

The answer would appear to be that the contractor should only submit change proposals when his own cost-effectiveness analysis says they're worth doing. If he's right BuShips will agree. Or at least BuShips should use such analysis to decide on their disposition.

RELIABILITY ACQUISITION COST



3 PROGRAM PLAN

Adequate and economical system reliability is achieved by doing the right thing at the right time. It is a characteristic which cannot be imparted at any one point in the program, but which can be destroyed by one error of omission or commission. To control system reliability, then, the reliability consequence of every design decision in system and hardware development must be clearly recognized and provision made to get the right result. This implies a level of detail in technical and program management which is very difficult to achieve in the traditional communication network of industrial management.

The formal Program Plan, therefore, has been found necessary for management (a) recognition of the real requirements, (b) assurance that the necessary tasks are planned, scheduled, funded and accomplished on time, (c) technical visibility of the ultimate consequence of alternative design decisions, and (d) visibility, throughout design, of the probable result vs. requirements. Without such a plan reliability achievement is very expensive and ineffective.

The reliability and maintainability of a design is only what the design engineer puts there. It's very trite, but very true. Yet the reliability technology has become so complex, and the literature so voluminous, that the average design engineer cannot possibly learn all of it and still be a good design engineer. So industry has had to develop reliability and maintainability specialists to "support" the design engineer. But reliability support is an utter waste of money if it is not an integral part of the design program, and early enough for results to be used. This can be accomplished only by detailed planning based on intimate knowledge of the design.

The Reliability and Maintainability (or "Dependability") Program Plan should be the single instrument of detailed understanding as to exactly what will be accomplished to achieve required reliability and maintainability. Initially it constitutes Bureau agreement with higher authority. Then it becomes the Bureau agreement with the contractor. Finally it is the contractors comprehensive statement of his understanding of the problem, what he will do, how he will do it, when he will complete each item, and what manpower it takes.

Reliability program plans have been quite thoroughly developed ([illegible]) by many contractors over the past 5 to 10 years. Maintainability program plans have been only briefly developed, and they essentially parrot conventional reliability program plans. There has been some effort (8) to combine the two, but without much consolidation of tasks common to both. The following treatment covers both, and wherever one task will accomplish both it is so stated. This will minimize paperwork, cost, and confusion.

While BuShips may wish to add, delete, or alter many items of the contractors proposed plan, there absolutely must be agreement on its content and meaning before work starts. Keeping in mind that we have added the "(and maintainability)" wherever it is equally applicable, MIL-STD-785 states:

"3.1 Reliability (and maintainability) Assurance Program. The contractor shall establish and maintain an effective and economical reliability (and maintainability) assurance program, planned, integrated, and developed in conjunction with other planning functions. The program shall be adjusted to suit the type and (design, development, or production) phase of the procurement. The program shall be based upon the severity of the requirements, the complexity of the design, the quantity under procurement, and the manufacturing techniques required. The program shall assure adequate reliability (and maintainability) consideration throughout all aspects of the design, development, or production as necessary to meet the contractual reliability (and maintainability) requirements."

"3.3 Reliability (and Maintainability) Plan."

"3.3.1 Proposed Reliability (and Maintainability) Plan. The contractor's proposed reliability (and maintainability) program plan, in accordance with the requirements of the work statement and this standard, shall be submitted as a separate and complete entity within the contractor's proposal for the system. The proposed plan must be an integrated effort within the total program plan; it shall provide specific information as to how the contractor will meet specified quantitative reliability (and maintainability) requirements during development and manufacture including the design concepts to be utilized. The proposed manner of demonstrating reliability at stated confidence levels shall be described. The proposed reliability (and maintainability) program plan, as approved by the procuring activity will become a contract compliance document; reliability (and maintainability) test plans must be an integral part of the program test plan."

In order to encourage uniformity across proposals to permit valid evaluation, the Project Engineer may add these words:

"This Plan shall contain sections on (a) Requirements, (b) Program Charts, (c) Program Tasks, (d) Organization, and (e) Competence, as detailed below. The content of every section must state primarily (a) what will be done to be exactly responsive to BuShips stated requirements, then (b) the contractors alternative recommendation, if any, and then invariably (c) what portion thereof is already in contractor operation or has been done on past stated contracts."

"If the contractor is successful, all proposed sections (except Competence) will be negotiated in detail and, upon agreement, will become the contractual Program Plan. Though it may later be modified by mutual agreement, it is the sole contractual statement of reliability and maintainability work and results to be obtained."

The necessary content of the Program Plan, and especially the Program Tasks included, will vary widely depending upon (a) the gap between needed and available reliability and maintainability, (b) how well the available reliability and maintainability is known, and (c) the design level (system vs. parts). Figure 23-18 shows a recommended "starting point" for a very comprehensive program, but actual selection of tasks must rest on the specific situation. The table applies only to "critical" reliability and maintainability items as defined in Chapter 27. However, there may be many items of such low "criticality" (system failure rate increment due to that item) relative to others that such control of them may not be cost-effective. "Criticality", incidentally, is a numerical value on a continuous scale roughly equivalent to the stepped "levels of essentiality" and "classification of characteristics" used in quality control techniques where a prediction model is not available.

In an activity as urgent as that of reliability achievement, a tendency toward over-emphasis often occurs. Since much of the effort in such programs is support rather than design, its application to unnecessary areas can incur significant unneeded expense. Each Program Task must be weighed carefully in terms of its contribution to cost-effectiveness. Where Navy experience shows that traditional design practice or construction methods produce trouble-free hardware - such as perhaps is the case with internal bulkheads, for example - extensive reliability assurance activity is not warranted.

Even in areas of the design where there is some concern over reliability, task applicability will vary with the type of hardware. While great care may be needed in receiving inspection

RFP and PROPOSAL CONTENT

		For Systems and Subsystems (S), Hardware Components (C) and Parts (P)												Survey Evaluation (E)
		INSUFFICIENT RELIABILITY or Maintainability			NEW DESIGN Unknown Reliability or Maintainability			MATURE DESIGN, Widely used, Failures rare, Minor maint.			VERIFIED RELIABILITY & Maintainability at right environ.			
23:1.1	Environment & Stress	S	C	P	S	C	P	S	C	P	S	C	P	
23:1.3	Quantitative require.	S	C	P	S	C	P	S	C	P	S	C	P	
23:1.4	Applicable documents	S	C	P	S	C	P	S	C	P	S	C	P	
23:5.1	C-E analysis	S	C	P	S	C	P	S	C		S	C		
23:3	Program Plan	S	C	P	S	C	P	S	C	P	S	C	P	
23:3.1	Requirements	S	C	P	S	C	P	S	C	P	S	C	P	E
23:3.2	Program Charts	S	C	P	S	C	P	S	C		S	C		E
23:3.4	Organization	S	C	P	S	C	P	S	C		S	C		E
23:3.5	Competence	S	C	P	S	C	P	S	C		S	C		E
2 .3.3	Program Tasks													
A	Prog. Plan Update	S	C	P	S	C	P	S	C		S	C		
B	Education	S	C	P	S	C	P	S	C					E
C	Design to R & M	S	C	P	S	C	P							E
D	Apportionment	S	C		S	C		S	C					E
E	Prediction	S	C	P	S	C	P	S	C	P	S	C	P	E
F	C-E analysis	S	C		S	C		S	C					E
G	Failure modes & eff.	S	C	P	S	C	P	S	C		S	C		E
H	Stress/strength		C	P		C	P							E
I	Human factors	S	C		S	C		S	C		S			E
J	Design review	S	C	P	S	C	P	S	C		S	C		E
K	Parts control		C			C			C			C		E
L	Reports & review	S	C	P	S	C	P	S	C	P	S	C	P	E
M	Corrective action	S	C	P	S	C	P	S	C	P	S	C	P	E
N	Change & Config.	S	C	P	S	C	P	S	C	P	S	C	P	E
O	Supplier control	S	C	P	S	C	P	S	C	P	S	C	P	E
P	Mfg. R & M		C	P		C	P		C	P		C	P	E
Q	Failure diagnosis	S	C	P	S	C	P	S	C	P	S	C	P	E
R	Data acq. & red.	S	C	P	S	C	P	S	C	P	S	C	P	E
S	Verification	S	C	P	S	C	P	S	C					E

and process control for structural materials, with little emphasis on sophisticated reliability analysis, these latter techniques may prove most effective in disclosing opportunities for reliability improvement of electrical power supplies.

3.1 REQUIREMENTS

Reliability requirements are the foundation of every Program Plan. To date, the defense procurement record is bleak in terms of reliability requirements definition. Studies updated as recently as February 1964, indicate that less than one third of the system development programs in which reliability is stated to be an important factor specify this requirement adequately. The result is that system design and manufacture either ignore or grope around the edges of reliability technology, with neither customer nor contractor possessing a yardstick to measure achievement against. As in any activity, reliability and maintainability achievement, and the Program Plan, degenerate to pure motherhood and sin without quantitative, measurable goals.

The requirements stated in the Dependability Plan must be prefaced by adequate operational information. This includes such items as planned deployment, reaction time required, duration of each kind of mission, turn-around time, overall mission reliability, availability, combat ready rate, environmental conditions, and planned utilization rate. The broad operational maintenance philosophy and policy must be stated.

Although the BuShips reliability and maintainability requirements will have been stated to the contractors in the RFP, the contractor should be required to state them back in the Program Plan, with recommended modification, if any. The objective is to make very sure of common understanding and agreement on the baseline upon which all tasks are based. See Chapter 2. MIL-STD-785 states:

> "(3.5.1.1) If maximum environmental stress conditions have not been established by the procuring activity these shall be estimated from experience on past programs.....Detailed and specific review of environmental factors affecting reliability shall be performed."

Since environment and operational stress have a major influence on reliability achieved, the Project Engineer may wish to add:

> "The contractor shall evaluate the BuShips statement of operational environment and stresses, and recommend any specific

modifications thereof that in his own experience are appropriate. However the proposal must be based upon a least meeting stated environments and stresses."

Concerning quantitative requirements, MIL STD 785 states:

"3.2.1 Quantitative Requirements. The system reliability objectives and minimum acceptable requirements shall be as specified contractually. The minimum acceptable reliability requirements for some major subsystems and equipments may be included in appropriate sections of the system specification. The values not established by the procuring activity shall be established by the system contractor at a contractually specified control point prior to release of design for initial fabrication of specified articles."

The Project Engineer may wish to add:

"The contractor shall evaluate the BuShips statement of minimum (mandatory) and optimum quantitative reliability and maintainability requirements, and recommend any specific modifications he cares to make. However, the proposal must be based upon meeting the stated optimum requirements."

Concerning documents, MIL STD 785 states:

"2. Referenced Documents

MIL STD 721A	Definitions for Reliability Engineering.
MIL STD 756A	Reliability Prediction.
MIL STD 781	Test Levels and Accept/Reject Criteria for Reliability of Nonexpendable Electronic Equipment.
MIL HDBK 217	Reliability Stress and Failure Rate Data for Electronic Equipment
MIL STD 803	Human Engineering Criteria for Aircraft, Missile, and Space Systems, Ground Support Equipment."

Since the applicability of the above documents to most specific proposals will be very spotty indeed, the Project Engineer should add the appropriate paragraph numbers. He may also state:

"The contractor shall acknowledge the BuShips list of specifications, standards, performance specifications, work statements, etc., and their required section numbers, in the Program Plan. Under each the contractor shall state (a) the required section numbers that are acceptable, (b) those for which modification is recommended, and the reason, and (c) additional sections recommended, and the reason. Then he shall add any other documents upon which his proposal is based, calling out applicable sections thereof and providing copies."

3.2 PROGRAM CHARTS

According to MIL STD 785:

> "3.3.3 Management and Control. The program plan shall include detailed listing of specific tasks, man-loading per task, and procedures to implement and control these tasks. It shall include a description of each task to be performed whether or not it is already documented in contractor directives, the organizational unit with the authority and responsibility for executing each task, the method of control to insure execution of each task as planned, and scheduled start and completion dates of each task. This data shall be in a form that permits technical auditing by the procuring activity. The information provided shall include the method of analysis to be used as a basis for achieving the proper balance of effort and resources from a reliability standpoint.....The designation of milestones, definition of inter-relationships, and estimation of times required for reliability program activities and tasks shall be employed as part of overall program control which applies the program techniques. If PERT (Program Evaluation and Review Techniques) is part of the program it shall be utilized."

In order to provide a practical index of all reliability and maintainability Program Plan tasks, as well as an auditable summary of their schedule and progress, the Bureau may develop and specify a management presentation system such as the following:

3.2.1 Task Number and Title: In Figure 23-22, all Tasks discussed in chapter 22 have been listed and given an index letter for easy reference. The Project Engineer may specify in the RFP:

> "The contractor shall provide and maintain a one- or two-page Task Identification chart which lists the title of every Program Task to be undertaken, preceded by a reference letter or number thenceforth always used to designate that task. Tasks shall be listed in the approximate sequence to be undertaken, as in Figure 23-22."

TASK IDENTIFICATION

Document Section		TASK		Output (Events)		Responsibility		Man-Weeks
Std 785	M 313A	No.	Title	Number	Document or Result	Prime	Support	
3.3	3.1.1	A	Program plan update	1-8	8 revised plans	RE	DE, FI	32
3.5.8	3.1.1.1	B	Education	9-12	200 certificates	RE	DE	120
	3.1.1.2,3	C	Design to R & M spec	13-32	20 design reports	DE	RE, TF	160
		D	Analysis-Apportionment	33-40	8 revision reports			
	3.1.1.4	E	Model & prediction	41-64	24 revision reports		(etc.)	
3.2.2	3.2	F	Cost-effectiveness	65-72	8 revision reports			
		G	Fail modes & effects	73-76	4 analysis reports			
		H	Stress/strength	77-90	14 analysis reports			
3.5.9		I	Human factors	91-96	6 analysis reports			
3.5.6	4.5	J	Design review	97-136	40 DR reports			
3.5.3		K	Parts control	137	100 actions/month			
3.4	3.4	L	Summary reports	138-161	24 progress reports			
3.5.3.2		M	Corrective action control	162-209	48 CA needle reports			
		N	Change & config. control	210-249	40 Change approvals			
3.5.7		O	Supplier control	250-282	33 Supplier evaluations			
3.5.14		P	Mfg R & M control	283-306	24 Audit reports			
		Q	Failure diagnosis	307-367	61 Failure diagnoses			
3.5.15		R	Data acquisition	368-391	24 Handbook revisions			
3.5.1,16	4.3,4	S	Verification	392-476	85 Approved Verifications			

3.2.2 Document Sections: Since many specifications contain overlapping requirements, this chart provides the cross-index of multiple call-out, as well as easy reference to specification section numbers:

"The contractor shall provide a column for each major document that requires reliability or maintainability tasks, listing in each the document section numbers applicable to each task."

3.2.3 Output: Unless the output or tangible end-product of each task is clearly identified, there is no way for either BuShips or the contractor to audit accomplishment. This requirement is intended to neutralize Parkinson's third law. It is not so uncommon to find groups performing tasks whose output, if any, nobody needs:

"The contractor shall provide for each task (a) the name of its principal output (identifiable end result), (b) the number of such outputs to be produced, and (c) a unique output number range assignment for schedule identification. If there is more than one significant kind of output, another line may be used. The Task Delineation (chapter 22) must state who uses each output."

3.2.4 Responsibility: One of the prime problems in many reliability programs is undetermined, contested or weak responsibility and authority, leading to redundant costs and loss of good people. One way to cause contractor management to face up to unequivocal decision is to require clear statement in the reliability and maintainability Program Plan of exactly who is responsible for each task and gets replaced if it doesn't go well. It also tells BuShips who to put the finger on.

"The contractor shall provide a column showing by code letters (such as the organizational group name initials) exactly which one group has responsibility and authority for the task, and which other groups will expend support manhours."

3.2.5 Manpower: Relative effort to be applied to each task provides an important clue to contractor understanding of work content, and of course is necessary during negotiation to fix exact task content. And sometimes the cost of reliability achievement will be an eye-opener to BuShips personnel, but must be balanced via cost-effectiveness analysis against the potential maintenance manpower.

"The contractor shall provide a column showing the total manweeks required to produce all outputs for each task for the entire program."

3.2.6 Task Schedule: During the proposal phase this provides some evidence that the contractor has thought through the timing of each task output relative to the design and production schedules. As design gets underway it provides a convenient means of visualization and audit of contractor progress.

"The contractor shall provide on a separate page a Task Schedule chart such as Figure 23-25 with a column of short task titles and their numbers in the same sequence as in 3.2.1 above, with week numbers across the page top, identifying key contract weeks by date. The chart will show under each week number, opposite each task, the task start week(s) and output numbers as they will fall due, all such due dates being events that must be consistent with the overall PERT/Cost network."

3.3 TASK DELINEATION

A comprehensive reliability and maintainability program for a large program contains a few dozen fairly distinct Tasks, the principal ones being listed in chapter 22. Lesser emphasis and/or smaller projects require fewer elements and/or less depth of effort within the elements. The contractor should be encouraged to state his own estimate of the tasks and depth needed to satisfy the stated requirements, yet always show adequate consideration of the tasks listed in chapter 22. Again referring to MIL STD 785:

"3.3.3 Management and Control. The program plan shall include detailed listing of specific tasks, man-loading per task, and procedures to implement and control these tasks. It shall include a description of each task to be performed whether or not it is already documented in contractor directives, the organizational unit with the authority and responsibility for executing each task, the method of control to insure execution of each task as planned, and scheduled start and completion dates of each task. This data shall be in a form that permits technical auditing by the procuring activity. The information provided shall include the method of analysis to be used as a basis for achieving the proper balance of effort and resources from a reliability standpoint....The designation of milestones, definition of inter-relationships, and estimation of times required for reliability program activities and tasks shall be employed as part of overall

TASK SCHEDULE

TASK		OUTPUT DUE DATES, weeks after BuShips authorization																													
No.	Short Title	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
A	Program plan	3					2													3											
B	Education	S			9	10	11	12																							
C	Design, R & M			S												13					14			15				16	17		
D	Apportionment		S		33													34													
E	Prediction		S			41				42				43					44				46				47				48

> program control which applies the program techniques. If PERT (Program Evaluation and Review Techniques) is part of the Program it shall be utilized."

Thus in relation to the contractors tasks, the Project Engineer may specify:

> "For each of the Tasks listed in (chapter 22), the contractor shall (a) state whether or not effort on this task is planned, and if not why not; and if planned (b) describe concisely how the task will be accomplished, showing the depth of detail anticipated, (c) state what tangible or recognizable and auditable output will be produced, and (d) state what specific organizational groups will use the output and for what purpose. Do not use more than one-half to one page per task."

> "Then the Program Chart (section 3.2 above) shall show (e) what document sections call it out, (f) what groups are responsible for doing and supporting the work, (g) what manpower (manweeks) is required, and (h) when each successive output is scheduled due."

3.4 ORGANIZATION

While BuShips cannot and should not dictate the contractors internal organization, it is nevertheless often a very important indication of his appreciation of the reliability and maintainability problem, and therefore his competence. See reference (9, secs. 4,5,6). MIL STD 785 states:

> "3.3.2 Reliability (and maintainability) Organization. The program plan shall (a) identify the organization and the personnel responsible for managing the overall reliability (and maintainability) program, and (b) shall clearly define its repsonsibilities and functions including both policy and action. It shall stipulate the authority delegated to this organization to enforce its policies. The relationships between line, service, staff, and policy organizations shall be identified."

3.4.1 Company Structure: Here the objective is to find out whether reliability and maintainability groups (a) actually exist, and (b) are close enough to design engineers to be effective, or whether they are "ivory tower" generators of procedures and reports that nobody reads and on which nobody takes action. Although such central groups are usually called "Reliability Engineering," there is a stron trend toward combining such activities and calling them "product" effectiveness, system effectiveness, or (recently) cost-effectiveness. In order to get proposal uniformity for evaluation purposes the Project Engineer may specify:

> "The contractor shall provide an organization chart showing (a) the major functional and project groups reporting to the top executive, and (b) a line of authority breakdown to those engineering, reliability, and maintainability groups that will directly contribute to the program. The latter must show every supervisory level in the hierarchy, identifying the working groups (the order of 5 to 20 people) with code letters or numbers called out in the Program Chart (section 3.2.4) responsibility column."

> "Each organizational block must show the name of the group, the name of its supervisor, and the total number of its personnel, using parentheses around each planned but not existing entry.

3.4.2 Policy Direction: Not much gets accomplished until the top executive or his top subordinates issue directions in unequivocal and clear terms. Such directives are usually signed by the top executive and state what is to be accomplished, by whom, and how he verifies that it gets done. The Project Engineer may specify:

> "The contractor shall provide [illegible]py or quotation of the reliability and maintainability policy directives and standard procedures binding upon all engineering, reliability and maintainability personnel, with signature, title, and date. He shall include both company-wide directives and procedures and those, if any, concerning this program, and state how he assures that they are kept current and complied with."

3.4.3 Responsibility and Authority: The design engineering groups must have the final decision on all design decisions, or else they could not be held accountable for their designs. Yet there must be procedures whereby such decisions cannot be made until there is adequate consideration of reliability and maintainability impact. In most cases the design engineer is too close to his design to be a good judge of such adequacy, so the reliability and maintainability groups must review every new design and make recommendations, if any.

If the design decision is contrary to such a recommendation, which should be rare, there must be independent channels by which the recommendation can be taken up the hierarchy for reconsideration, even by the top executive in rare cases. For comprehensive programs the Project Engineer may specify:

"Referring to the Organization Chart (3.4.1), the contractor shall briefly list the responsibilities and authorities assigned to design vs. each reliability and maintainability group in matters concerning reliability and maintainability achievement, analysis, and verification. The contractor shall explain the flow of work between such groups, and state how differences of opinion are resolved. He will specifically list the documents that require reliability/maintainability group (a) review, and (b) signoff.

3.4.4 Program Control: Unless a specific group has the responsibility for keeping track of task performance, keeping task progress in balance, and directing relative task effort accordingly, schedules will certainly slip and reliability suffer. The Project Engineer may wish to be more specific:

"The contractor shall name the group responsible for reliability/maintainability program control, and state the procedures it will use to keep task progress in balance and on schedule, and to direct relative effort apportionment thereon."

3.5 COMPETENCE

Often a contractor will seem to thoroughly understand the problem, and will propose an excellent program plan, yet make many costly and schedule-slipping mistakes before producing the required reliability and maintainability. There is no substitute for experience, and the RFP must require the proposal to provide quite specific answers.

3.5.1 Programs: Until a contractor has had to design to specified reliability and maintainability, he usually considers it a big propaganda and quality control drive. In order to ferret out exactly what a contractor has accomplished the Project Engineer may specify:

"The contractor shall list the programs he has undertaken which contractually required (a) design to specified reliability and/or maintainability quantitative values, (b) design to "high" reliability requirements, or (c) design and production with execution of specific reliability Program Plan tasks. For each the contractor will state, if known, how the achieved quantitative reliability and/or reliability compared to values predicted in the initial Program Plan."

3.5.2 Technology Development: Many progressive companies develop their reliability and maintainability technical capability by funding long-term research projects or by funding shorter-term projects that will challenge and hold their best people between programs. To identify this latent capability, the Project Engineer may specify:

"The contractor shall list and briefly describe the reliability and/or maintainability technique research or development projects he has undertaken either on contract or company funding, and for each the actual application of results."

3.5.3 Industry Participation: The extent of participation in government and industry committees and conferences is also an indicator of company appreciation of the problem and contribution to its solution. The Project Engineer may specify:

"The contractor shall list the reliability and/or maintainability government and industry committees on which he is represented, and for each the name and company position of his representative. The contractor shall also list the reliability, maintainability, system effectiveness, and cost-effectiveness papers and conference sessions prepared or moderated by his personnel during the previous year, and for each the person's name and position."

3.5.4 Resumes: Most proposal resumes do not indicate the experience that personnel may have had in design for reliability and maintainability, though analysis experience is covered. The Project Engineer may specify:

"The contractor shall provide one-third-page resumes on each of the key personnel that will be responsible for achievement of required reliability and maintainability. These should include design as well as reliability and maintainability people, stating their reliability and maintainability design, analysis, and supervisory experience."

3.5.5 Task Experience: Nearly all proposals will contain proposed tasks that the contractor has never done before. Often as not he may consider them as unnecessary embellishments, but of course wants to be strictly responsive to the RFP. Since prior experience has a great effect on his understanding and support of the task, there must be some way to identify such task experience. As stated in section 3., all Task delineations in chapter 22 must state what portion thereof is already in contractor operations or has been done on past stated contracts.

3.5.6 <u>Supplier Competence</u>: It is one thing to propose an excellent program with tasks that subcontractors and vendors are expected to accomplish, but quite another to get some of them to cooperate. Even when the contractor carefully discusses reliability and maintainability requirements with every significant supplier prior to assembling his proposal, there have been many serious problems after award when the supplier says "I didn't think you really meant it!" or "Oh, is that what you meant!" The Project Engineer may develop confidence in the contractors selection of suppliers by specifying:

> "The contractor shall provide evidence of the competence and willingness of his proposed suppliers of critical components to conduct the tasks he prescribes. Copies of supplier letters acknowledging the reliability and maintainability requirements and expressing management willingness to perform the necessary tasks will suffice."

3.6 SHIPBUILDING PROCUREMENTS

A complex specification situation occurs in a major procurement such as a class of ships. The detail specification for the ship class provides the requirement for equipment with environmental conditions, operating conditions and installation conditions. Weight, space, and size limitations on the various equipments may be defined. Systems to be installed in the ship may be procured by the government or the shipbuilder. Those systems purchased by the government are, in general, systems that are used in many applications. The selection of specification clauses and requirements must be reviewed to assure that:

(a) The environment specified in the equipment specification is compatible with its planned use in the ship;

(b) The reliability specified is compatible with the operating requirements;

(c) The maintenance philosophy (types and numbers of skilled personnel, spares allowance, level of repair) is compatible with the situation outlined in the ship specification.

The systems procured by the shipbuilder must also be considered as having an impact on the reliability of government furnished systems and on the effectiveness of the ship. The quantitative requirements, level of reliability control, and means of assessing the achieved reliability and maintainability must be specified for these systems furnished by the shipbuilder. Quality control provisions, although they have little impact on the design reliability, must be specified to assure that the operational reliability is not degraded below an acceptable level.

4. PROPOSAL EVALUATION

After the reliability and maintainability portions of the RFP have been prepared using the appropriate language as discussed above, it is issued to the selected contractors. Their questions are consolidated and handled in a bidders conference that specifically invites contractors reliability and maintainability personnel. Then the Project Engineer refines the detailed proposal evaluation criteria and organizes to handle the reliability and maintainability sections of the proposals when they come in.

Proposal evaluation, it goes without saying, is a very complex and very difficult subject. Evaluation techniques run all the way from sincere but subjective judgment of a perhaps unwittingly biased evaluator, to very complex numerical systems that generate precious little understanding and confidence in their result. But we must take into account quantitative contributions to the extent feasible.

Now what, precisely, constitutes the "best" proposal? It would be easy to say it is the one that will give us the best cost-effectiveness, and we'd be dead right. But we are not quite ready to use the DOD cost-effectiveness criteria, so it is discussed separately in section 5.3 et al. Let us discuss an approach which will help compare contractors apparent adequacy of proposed programs for what they say will be achieved.

4.1 BROAD EVALUATION

First we will have a look at the broad aspects of the contractors proposal, quantifying wherever feasible, after which we will evaluate his detailed tasks.

4.1.1 Cost-Effectiveness Analysis: For such provisions, useful at a future date, see section 5.4.1.

4.1.2 Program Requirements: As discussed in section 3.1, it is imperative that the contractor thoroughly understand the requirements. These evaluation questions may be used:

	Weight	Rating
1. Are the stated environments and stresses fully responsive?	20	
2. Are the proposed modifications thereof desirable?	20	
3. Are the environments and stresses adequately considered in design and analysis approaches?	40	
4. Are the stated reliability and maintainability requirements fully responsive?	40	
5. Are the proposed modifications thereof desirable?	20	
6. Are the stated applicable documents, including MIL STD 785, and sections thereof fully responsive?	40	
7. Are the proposed modifications thereof desirable?	20	
Total	200	

4.1.3 Program Planning: As discussed in Section 2.1.3 and 3. on Program Plans, and Sections 3.2 on Program Charts, we can evaluate the plan as a whole:

1. Are all necessary tasks listed on the charts?	25	
2. Are columns provided for all appropriate major documents?	15	
3. Are the appropriate document section numbers referenced?	10	
4. Is there a single responsibility shown for every task?	25	
5. Do the manweeks for each task seem reasonable and sufficient, and are funds allocated for all of them?	50	

		Weight	Rating
6.	Do the total manweeks seem reasonable, compared to a typical range of 5 to 20% of engineering manhours?	25	
7.	Does the timing of task outputs seem reasonably relative to each other and to the design and production schedule?	15	
8.	Has every listed program task been considered, and adequate reason given for those not planned?	10	
9.	Is there a concise description that gives a good picture of the depth planned for each task?	50	
10.	Is there a clearly identifiable, tangible, auditable output for every task?	50	
11.	Is there a statement of what specific groups will use the output of each task, and does it seem reasonable?	25	
	Total	300	

4.1.4 Organization: As discussed in Section 3.4, BuShips must take a close look at the implications of the contractors existing and proposed organization:

		Weight	Rating
1.	Is there an existing, as well as proposed, reliability and/or maintainability group?	100	
2.	Does it report high enough to attract and hold first-class engineers?	50	
3.	Is it independent or part of the engineering organization, as opposed to quality control or factory operations?	50	
4.	If there are any past or present deficiencies, will they be remedied by the proposed organization?	50	

	Weight	Rating
5. Has the top executive or the top engineering manager issued policies clearly requiring engineering design use of the reliability and maintainability technology? Are these supported by adequate department policies and procedures?	50	
6. Do contractor reliability and maintainability groups have the authority to make analyses and recommendations concerning all designs and design changes, <u>only after</u> which design decisions can be approved?	100	
7. Is there an independent channel whereby design decision contrary to recommendation can be taken up the hierarchy for reconsideration, by the top executive if necessary?	50	
8. Is the work flow between design and reliability/maintainability groups reasonable and sufficient?	50	
Total	500	

4.1.5 <u>Competence</u>: As discussed in section 3.5, we must heavily weight evidence that the contractor has faced similar requirements before, and can make available the technical and management people who know what works and what does not:

1. Has the contractor done much design to quantitatively specified reliability and maintainability, giving specific examples?	50	
2. Has he done much design to "<u>high</u>" reliability requirements, giving specific examples?	100	
3. Has he done much design and production involving execution of specific reliability <u>Program Plan tasks</u>, giving specific examples?	50	
4. Has he achieved the reliability values predicted initially?	100	
5. Has he undertaken many reliability and/or maintainability research projects whose results were put to work, and will they continue?	50	

	Weight	Rating
6. Are his people active in government and industry committees and conferences?	50	
7. Will the contractor use key design engineers on this program who have had reliability and/or maintainability design experience?	150	
8. Are the backgrounds of the planned reliability and maintainability specialists adequate for program?	100	
9. Has the contractor performed, or is he performing for other programs, nearly all of the required tasks to about the same depth?	100	
10. Does his understanding of tasks not previously performed seem adequate?	50	
11. Is there adequate evidence that all critical component suppliers are competent and willing to undertake the proposed reliability and maintainability tasks?	200	
Total	1000	

4.2 TASK EVALUATION

Having covered the broad aspects, we can turn our attention to the detailed tasks called out by Figure 23-22 in section 3. and the Task Delineation in Section 3.3, discussed in detail in chapter 22. All weights shown in this section will later be multiplied by a factor of up to 15, depending upon completeness of response, in the final evaluation summary. Other weights may of course be used instead, but it should be kept in mind that emphasis will vary very widely, depending upon the background experience of those who select weights. The following evaluation questions may be used:

	Weight	Rating
1. Program Plan Update:	10	
Is a reasonable update program proposed?	10	
Total	10	
2. Education:		
a) Is there an adequate management reliability and maintainability indoctrination program?	10	

	Weight	Rating
b) Is there an adequate design engineering reliability and maintainability training program?	10	
c) Are concise reliability and maintainability reference manuals provided to engineers, as well as selective current literature on new methods?	10	
Total	30	
3. Design to Specified Reliability and Maintainability:		
a) Does the design indicate depth of understanding of the reliability and maintainability problem?	5	
b) Will the design meet the reliability and maintainability requirements?	10	
c) Is the proposed design quantitative reliability and maintainability optimum for best cost-effectiveness, the available tradeoffs having been executed?	15	
d) Are maintenance, logistics, training, etc. requirements adequately considered?	5	
e) Will all design specifications for critical components and changes or modifications thereto contain (1) reliability and maintainability requirements, (2) verification criteria, (3) protective packaging requirements, (4) traceability identification, and (5) operating, storage, and transportation environment?	10	
f) Are requirements beyond state of the art identified correctly?	10	
g) Are components of inadequately-known reliability identified correctly?	10	
h) Do the proposed design solutions show adequate knowledge of available approaches?	10	
i) Is adequate rationale given for the planned approaches?	10	

	Weight	Rating
j) Is the verification method and criteria stated for each case?	15	
Total	100	
4. Apportionment:		
a) Is the basis of apportionment of availability, reliability and/or maintainability logical for the missions required?	2	
b) Is the apportionment based upon best available information according to the reliability group?	3	
c) Is the apportionment mathematically correct?	2	
d) Does it show any critical problems not identified in 3. above?	3	
Total	10	
5. Model and Prediction:		
a) Is the model adequate for the system and missions required?	5	
b) Does it account for human reliability and maintainability, if they are involved?	5	
c) Is the model supported by a practical data update system?	10	
d) Is there adequate provision for continuous update and monthly predictions and comparison with apportionments?	10	
e) Is design action required as a result of adverse prediction?	10	
Total	40	
6. Cost-Effectiveness Analysis:		
a) Is there provision for quarterly update of system prediction?	5	
b) Is there provision for reporting regularly the total cost saving that would result from 2-to-1 MTBF or MTTR improvement?	5	

	Weight	Rating
c) Is design action required as a result of analysis indicating improvement opportunities?	10	
Total	20	
7. Failure Modes & Effects Analysis:		
a) Will an analysis be conducted on every component, or something less?	5	
b) Is a procedure described for identification of causes, modes, and effects of each potential failure?	5	
c) Will the analysis be updated quarterly?	5	
d) Is design action required as a result of analysis indicating improvement opportunities?	5	
Total	20	
8. Stress/Strength Analysis:		
a) Are such analyses planned wherever feasible, or just where failure data is not obtainable, or not at all?	5	
b) Is design action required as a result of analysis showing inadequate reliability?	5	
Total	10	
9. Human Factors:		
a) Where there is a choice, is there adequate consideration of the choice between human and hardware components?	2	
b) Will human engineering principles be applied adequately to displays and controls for the operators?	3	
c) Will human engineering principles be applied adequately to design for maintenance?	2	
d) Is design action required as a result of human factors analysis indicating less than optimal design?	3	
Total	10	

	Weight	Rating
10. Design Review:		
a) Will documented design review be conducted on all new designs, design changes, and cases of unknown or suspect reliability, or something less than this?	10	
b) Will they be conducted at both conceptual and prior-to-release phases?	5	
c) Are they scheduled and budgeted so that there will not be difficulty getting expert participation?	5	
d) Are design checklists to be made available to design engineers prior to design, for their required use?	5	
e) Is consideration of quantitative reliability and maintainability required in every review?	5	
f) Are recommendations required to be carried as Corrective Action log items until resolution satisfactory to reliability and maintainability specialists?	5	
g) Is participation limited to small, effective teams primarily of specialists from other than the responsible design group, but specifically including reliability maintainability and design group representation?	5	
Total	40	
11. Parts Control:		
a) Does the contractor have an effective preferred parts control program?	10	
b) Does the parts group control non-preferred parts qualification and approval?	5	
c) Does it always participate in Design Review of parts assemblies?	5	
d) Does it provide application assistance (such as derating) and data to design engineers?	5	

	Weight	Rating
e) Does it write all parts specifications to DOD format?	5	
f) Does it control parts handling procedure?	5	
g) Does it control traceability identification?	5	
Total	40	
12. Summary Reports:		
a) Is there an effective reporting system that keeps each design supervisor advised of the predicted quantitative reliability and maintainability of his design, compared to the apportionment?	5	
b) Is there an effective system of such quantitative reporting to contractor management and to BuShips?	3	
c) Is there an effective system to audit and report monthly progress on all tasks of the Program Plan?	2	
Total	10	
13. Corrective Action Control:		
a) Does the contractor have a system to assign individual responsibility for corrective action on every prediction/apportionment discrepancy, with regular reporting until resolved?	5	
b) Does it apply to every design review recommendation?	2	
c) Does it apply to every production and operational failure?	3	
Total	10	
14. Change & Configuration Control:		
a) Does the change control system require invariable consideration of quantitative effect on reliability and maintainability?	5	

	Weight	Rating
b) Does it require such effect to be incorporated into the model?	5	
Total	10	
15. Supplier Control:		
a) Are pre-award surveys made of supplier design engineering reliability and maintainability capability, and the design and analysis techniques employed?	5	
b) Do the pre-award surveys evaluate supplier management understanding and support, and existing conduct of necessary tasks?	5	
c) Do the pre-award surveys evaluate achieved quantitative MTBF and MTTR?	5	
d) Are cost-effectiveness analyses (reliability vs. cost) conducted prior to or during supplier negotiations?	5	
e) Does the contractor include quantitative reliability and maintainability requirements in every procurement of a critical component, as well as the verification criteria?	5	
f) Are specifications, including environments and maintenance requirements, issued for all critical component procurement, as opposed to order by catalog number?	5	
g) Are monthly predictions of reliability and maintainability required from every supplier on critical components?	5	
h) Are monthly progress reports required on each supplier Program Plan task?	5	
i) Are resurveys regularly scheduled on all suppliers, and current reliability and maintainability ratings (not quality ratings) maintained?	5	
j) Is supplier design action required for adverse predictions and verifications?	5	
Total	50	

	Weight	Rating
16. Manufacturing R & M Control:		
a) Is there adequate control permitting only known-reliability parts to get into assemblies?	3	
b) Is there adequate handling control?	2	
c) Is there adequate traceability by serial or lot number?	3	
d) Is there an adequate log of every test?	2	
Total	10	
17. Failure Diagnosis:		
a) Is there mandatory provision for every component failure to be recorded throughout design evaluation, production, test, checkout, and operational use?	5	
b) Is every such failure diagnosed for cause, mode, and effect, with adequate facilities available?	5	
c) Is design action always required, wherever it can help to prevent recurrences?	5	
d) Will the contractor provide diagnoses after delivery, in operational use?	5	
Total	20	
18. Data Acquisition and Reduction:		
a) Is there an adequate continuous data acquisition system utilizing data from suppliers, design, manufacture, trained field collectors, industry, and particularly the Navy (GFE and operational use)?	5	
b) Is there an adequate continuous data reduction system, with component reporting in convenient form for design engineers day-to-day use?	5	
Total	10	

19. Verification:

	Weight	Rating
a) Is a complete list provided of components to be verified, and does it seem reasonable?	10	
b) Are the tests adequately specified, properly accounting for environment, and are they reasonable, practical and economical, using available facilities?	15	
c) Are the verifications by other than test the best practicably achievable?	5	
d) Is there an integrated test plan to get the most information from the least number of tests, and is it related adequately to the design and production schedule?	10	
e) Is design action required whenever verification is not obtained?	10	
Total	50	

4.3 PROGRAM PLAN RATING

Fully recognizing the wide variability that may be encountered both in establishing weights and in entering an evaluation figure for each question, the errors of the procedure tend to balance each other out. With eyeball attention to over 100 questions, and there are this many things deserving of attention, such a rating system will quite consistently separate the good from the bad. Of course we should not expect to depend upon it as the sole evaluation of the Program Plan, particularly when total ratings are within 10% of each other, but it does provide a powerful basis for good human judgment.

Figure 23-44 is a chart that may be executed independently by each evaluator for each contractors proposal, followed by discussion and averaging for a final chart on each contractor. As the evaluator reads each task of the proposed program plan, he asks himself each of the specific questions listed in section 4.2 above. Then he enters a summation figure for each, and records it as Y in the Specific Content Rating column of Figure 23-44. As an example, 28 is entered for "0" Supplier Control.

Then he checks back for completeness of that task statement, asking himself the questions in section 3.3, and entering an

PROGRAM PLAN RATING

Task Delineation Completeness. See section 3.3

Why or Not	How & Depth	What Output	Who Needs	Docum Sectn	Who Does	Man-power	Sched Outpt	Total Mult.	TASK	Specific Content Rating	Composite RATING Wt	Composite RATING Total	MAN-WEEKS
1	3	2	2	1	2	2	2	X(15)	weight	Y	XY	XY	
									A Plan update		150		
									B Education		450		
									C Design		1500		
									D Apportionment		150		
									E Model, predic.		600		
									F CE analysis		300		
									G Failure effects		300		
									H Stress analysis		150		
									I Human factors		150		
									J Design review		600		
									K Parts control		600		
									L Reports		150		
									M Correct. action		150		
									N Change control		150		
1	3	1	1	1	2	2	0	11	O Supplier control	28	750	308	160
									P Mfg. control		150		
									Q Failure diag.		300		
									R Data acquis.		150		
									S Verification		750		
									TASK TOTAL		7500	3772	
									Cost-effectiveness analysis		500	320	
									Program requirements		200	185	
									Program planning		300	300	
									Organization		500	450	
									Experience		1000	665	
									TOTAL		10000	5692	
									PROGRAM RATING %			57	

CONTRACTOR: ____________________

evaluation for each. The example for Supplier Control adds up to 11 which, multiplied by 28, gives 308 for the Composite Rating. Manweeks are entered from the Chart (section 3.2) to get a feel for relative effort. This is done for all tasks, to get a Task Total, 3772 in the example.

Similarly the questions in section 4.1 are asked, the results entered below the Task Total, for a grand total. Dividing the example total of 5692 by 100, the Program Plan Rating is 57%.

Let's be careful about the meaning of this rating. It does not mean the evaluator thinks the contractor will do only 57% of what he ought to do. It does mean that he thinks the contractor plans to do about 57% of all possible things that could be done. If the contractor can justify not doing them, and still convince BuShips that he will more than meet requirements, so much the better.

But at the same time the rating is a measure of the strength of the reliability/maintainability program proposed. And the higher the Availability or Reliability proposed, relative to the state of the art, the higher the rating should be. This of course suggests taking a ratio of rating to Availability, as a measure of confidence that the contractor can indeed achieve the proposed values. Such a "Confidence Rating" is used below.

4.4 EVALUATION SUMMARY MATRIX

Now that we have organized the result of each contractors proposals, and evaluated the results of each on a consistent basis, we must evaluate them relative to each other. Figure 23-46 shows a matrix that can be used. Across the top we provide columns for each contractors response to BuShips stated requirements, and then another set of columns for contractor-recommended alternatives. Down the left side we call for the Confidence Rating discussed above, and below that its key constituents, for easy reference.

Now we look at the Confidence Rating, which compares Program Plan Rating Z to the expected Availability A. Contractor "A" proposed a program to get substantially higher Availability of 80% vs. required 70%, by taking 5 months longer, with something less than the anticipated Program Plan strength, so the Confidence Rating dropped to 71%. Contractor "B" proposed unheard-of Availability of 90%, taking 10 months to get it, but imposing a very strong 70% Program Plan. So the Confidence Rating is 78%.

EVALUATION SUMMARY MATRIX

			Requirement Response by contractor			Recommendations by contractor		
		Units	A	B	C	A	B	C
CONFIDENCE RATING	Z/A	%		86		71	78	
Availability Expected	A	%		70		80	90	
Delivery Effectiveness	D_r	%		100		95	90	
Program Plan Rating	Z	%		60		57	70	

Obviously these Confidence Ratings are very rough, only for use as guides. They are not statistical confidence probabilities of getting the stated values, and they can go over 100%. While more complex methods of relating Rating to Availability could be used, such refinement does not seem justified.

4.5 DE-BRIEFING

Nothing is quite as demoralizing to a contractors proposal leader and his team, who have put long hours and weekends into what they believe is an excellent proposal, than to be unable to find out why they lost the award. Unless they can find out what to do differently on the next one, they will have progressively less interest in bidding. And such attrition of competent bidders is not in BuShips long-term interests.

The debriefing conference should specifically invite a reliability/maintainability representative from each contractor, because experience has shown that others often do not understand the significance of what is said in this area, and fail to get the information needed. While the Bureau might say "That is the Contractors's problem, if he sent the wrong people," that fact is no help to reliability and maintainability needed in future proposals.

While specific deficiencies of any one identified contractor should of course not be discussed in front of others, that contractor does have the right to detailed private discussion of such deficiencies. The Bureau need not defend its decision, but can explain just what was deemed deficient in relation to the successful proposal.

There would appear to be no objection to giving a contractor his own ratings and average ratings for, say, the top three bidders. With these his management can forthwith get real motivated to take action on future reliability and maintainability programs.

5. COST-EFFECTIVENESS PROVISIONS

While the cost-effectiveness criteria are being inexorably inserted by DOD, and they form the very basis for nearly all reliability and maintainability decisions, they are not yet widely used. And they are very rarely used for hardware design decisions.

So that the above sections will be closer to the real world, we have separated out the cost-effectiveness provisions in this section. The numbers in parentheses are the above sections of which they would be a part. The Project Engineer is urged to use them whenever he sees an opportunity and advantage in so doing.

5.1(1.2) COST-EFFECTIVENESS ANALYSIS

Let's take a look at what DOD 3200.9 says (1) about cost-effectiveness in Figure 23-49. The principles apply equally well at all levels of the system, from the entire weapon system thru ships, down to parts.

Specification of reliability and maintainability requirements should never be permitted without a prior analysis of their true effect on system effectiveness and their consequent total cost, as discussed in chapter 26. As Rear Admiral Emerson Fawkes has said (10):

> "The cost of acquisition is like an iceberg; it fails to reveal the ownership cost of 4 to 10 times the acquisition cost."

Figure 23-50 shows the basic tradeoffs involved in using cost-effectiveness analysis to determine reliability and maintainability requirements. Such analysis results may not always be used directly, but they always provide remarkably better insight upon which to base good management judgment. The Project Engineer may therefore wish to:

> "Conduct a cost-effectiveness analysis of the system for the stated missions and anticipated lifetime environments and stresses, to determine the appropriate values of reliability and maintainability to be required of the contractors."

5.1.1 (2.1.2) Cost-Effectiveness Analysis: With analyses of system effectiveness vs. total long-term cost from several competent bidders, BuShips will be able to (a) verify or correct the reliability and maintainability quantitative requirements, and (b) better evaluate bidder competence. See chapter 26, section 7.2. But it is necessary for the Bureau to provide in the RFP the criteria for effectiveness and the necessary ownership cost factors, to put all bidders on a common basis except for their own estimates of acquisition cost. If such analysis is requested, as strongly recommended, the following RFP words may be used by the Project Engineer:

> "System effectiveness may be taken as the product of (a) performance capability measured by (state empirical formula),

DOD on COST-EFFECTIVENESS

Directive 3200.9

Project Definition Phase Prerequisites
VC, 5, 6

Normally, initiation of a PDP for an Engineering Development or Operational System Development will not be approved unless it appears that:

> The mission and performance envelopes are defined and are optimized for technical feasibility and cost-effectiveness. The cost-effectiveness of the proposed item has been determined to be favorable in relationship to the cost-effectiveness of competing items on a DoD-wide basis.

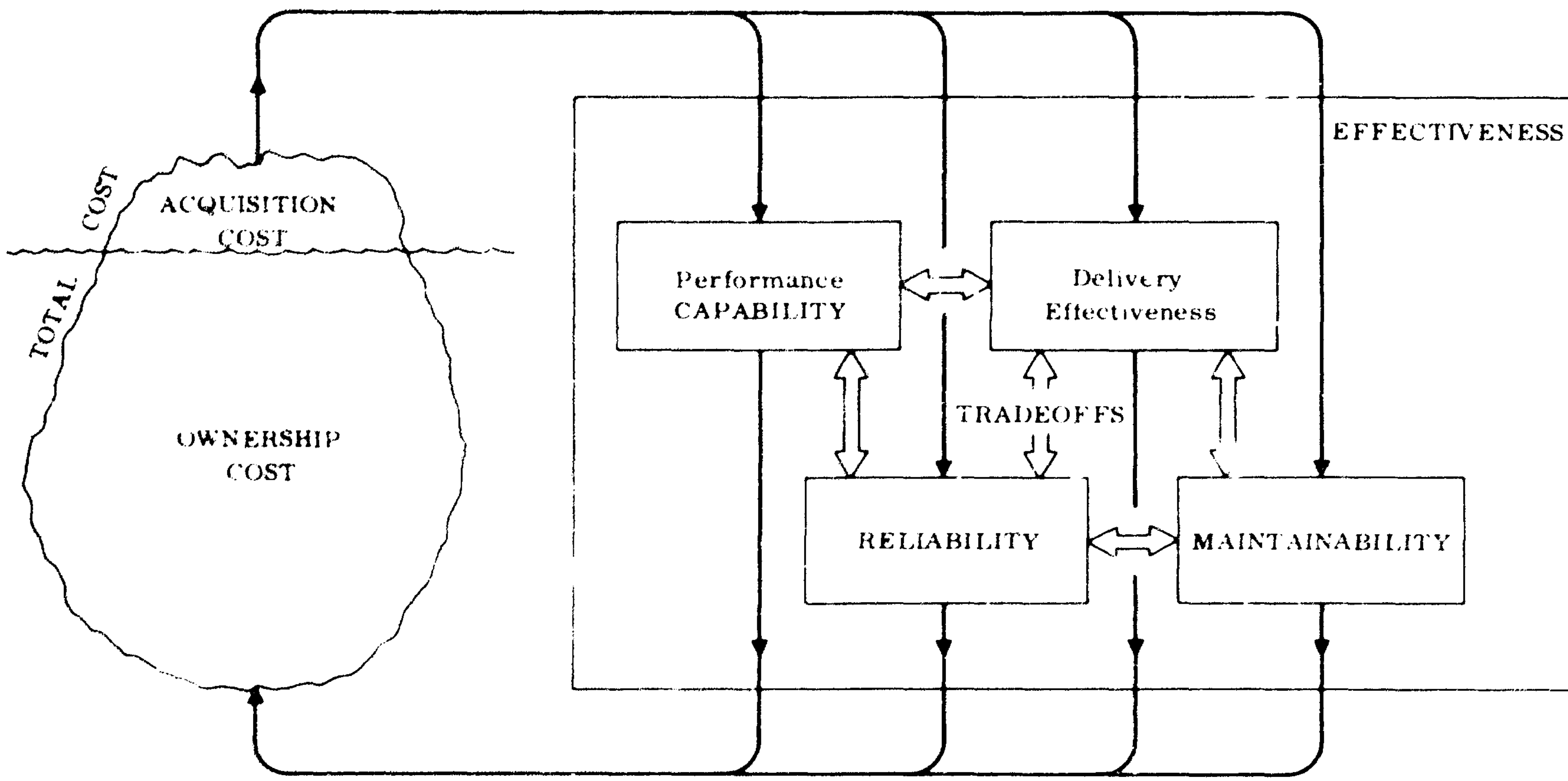
Total System Tradeoffs
VE4

Tradeoffs shall be used to obtain, within the mission and performance envelopes, an optimum balance between total cost, schedule, and operational effectiveness for the system.

In this context, total cost means the total cost of acquisition and ownership (development, production, deployment, operation, and maintenance); operational effectiveness includes all factors influencing effectiveness in operational use (such as "pure" performance, reliability and maintainability); and system includes the hardware itself and all other required items, such as facilities, personnel, data, training equipment, etc.

BASIC TRADEOFFS for COST-EFFECTIVENESS

How much reliability is required and justified?



(b) delivery effectiveness (state formula showing degradation vs. weeks delay), (c) operational availability (state formula combining demand and/or continuous availability and/or reliability) and (d) operational utilization (state formula showing weight for each kind of mission). The ratio of this product to total cost of acquisition (development and production) and ownership is to be maximized subject to (state any cost or other constraints)."

"Ownership cost may be taken as the total operational cost over (state useful life) years at (state hours) actual operation per year, including (a) operational cost of (state total $ per manhour for operator training, salary, facilities, etc.), (b) maintenance cost of (state total $/manhour for maintenance personnel training, salary facilities) plus the cost of spare components plus logistic at (state $ per pound for average components), and (c) consequence cost external to the system resulting from late delivery at (state $ cost, if any, per week of delay) and system failure at (state $ per hour down, including waste, damage, or loss of equipment, personnel, or other resources)."

"The contractor shall conduct an analysis to determine the reliability and maintainability that will achieve maximum system cost-effectiveness, over a range of reliability and maintainability on each side of the state requirements, explaining the method and summarizing results in the Program Plan, with a summary of the design and manufacturing differences by which such ranges would be obtained. Such MTBF (if used) and MTTR ranges should be 3-to-1 on each side of stated requirements. If the analysis indicates alternative requirements to be more cost-effective, he will recommend new values of reliability and maintainability, but base the entire Program Plan on the stated requirements."

"Based on the above analysis, the contractor will state what quantitative cost-effectiveness (a) will be achieved if he exactly meets BuShips stated requirements, and (b) would be achieved if his alternative recommendations are accepted. These estimates and the means by which they are derived, will be important considerations in award of the contract."

5.1.2 (2.4.4) Contracting for Cost-Effectiveness: There is no doubt in the minds of many people, including Dr. Hitch, DOD Comptroller (11) that the only ultimate solution is to contract for the best combination of cost, effectiveness, and delivery. And he agrees that delivery can usually be accounted for within cost and effectiveness. But we do not yet have procedures to do this.

What we do not want is the lowest proposed price (acquisition cost), because this will usually reflect the lowest (maybe zero) effort on reliability, consequently the poorest reliability and the highest long-term ownership cost, far offsetting the immediate saving. Figure 23-53 shows the result of a Navy survey (12) of 20 questions to 196 contractors in 1960, asking them to rank what they considered to be the deterrents to reliability. A similar Air Force survey produced the same result regarding funding.

Nor do we want "100% reliability," because it would cost more than it's worth, and besides it's impossible. What we do want is the most system effectiveness (performance, reliability or availability, and delivery adherence) in relation to total cost (contractors price plus lifetime ownership cost for delivery, delays, operation, maintenance, and failure consequence). Contracting for such a thing hasn't been done yet, but it's got to be done.

What can we do?

1. Carefully specify the target reliability and maintainability values, and how they will be measured. Then require the bidders to provide quotations for a range of reliability and maintainability surrounding the target values (See 1.4, 2.1.1)

2. Require the bidders to conduct their own analyses of the cost-effectiveness of what they propose to deliver. (2.1.2)

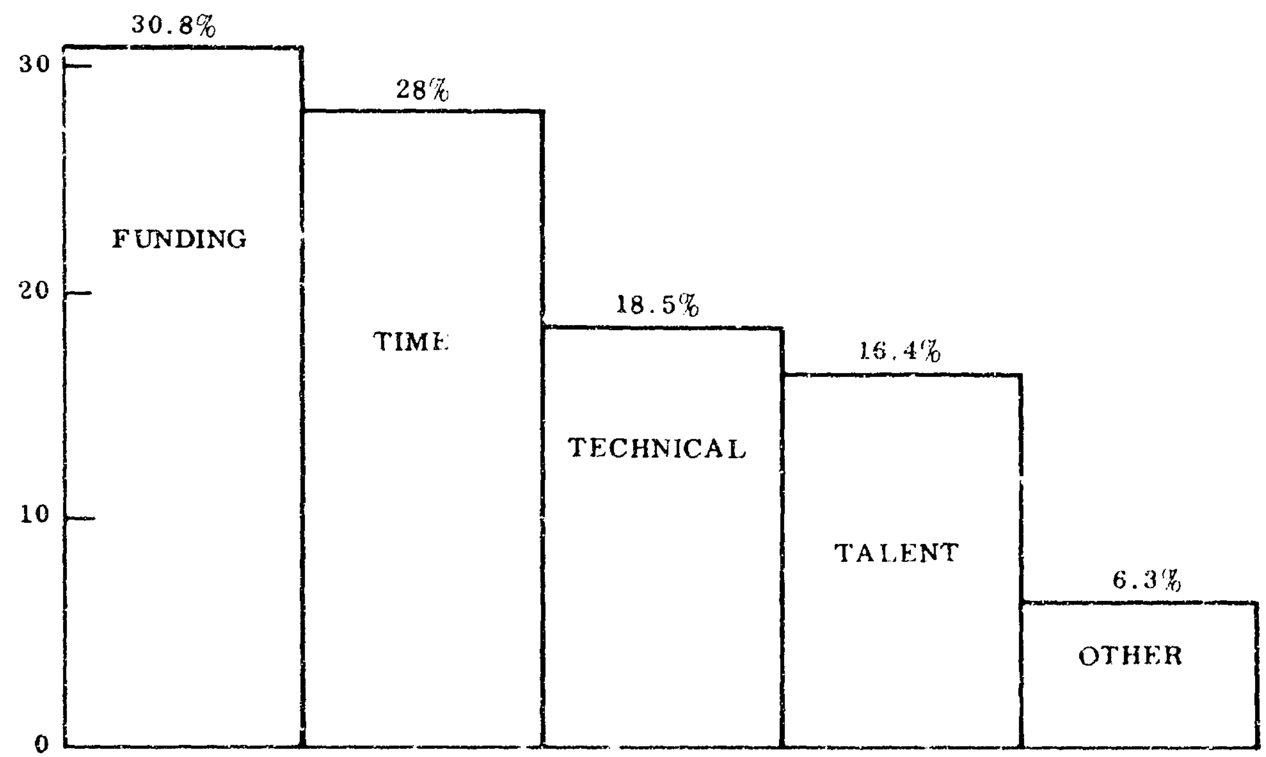
3. Award to the bidder proposing the best cost-effectiveness, from among those capable and whose analyses are convincing. (4.4)

4. Negotiate fixed-price-incentive contracts where the incentive is a fraction of achieved cost-effectiveness beyond target, with converse penalty. In this way the contractor can get paid for reliability improvement to the extent that it pays off, but not otherwise.

Value Engineering clauses (13,14), incidentally, have provided incentive for reduced Acquisition Cost but not for improved cost-effectiveness. It is almost common for such proposals to be disapproved because the reduced Acquistion Cost is more than offset by consequently higher Ownership Cost. While somewhat higher reliability usually results from the simplification, sometimes it does not, and the logistic consequence may be substantial in either case.

DETERRENTS TO RELIABILITY

US Navy BIMRAB Survey



5.2 (4.0) PROPOSAL EVALUATION

In section 4.0 we said the "best" proposal is undoubtedly the one that will give us the best cost-effectiveness. But even if we have cost-effectiveness analyses from several contractors showing what cost-effectiveness they will achieve, how do we know they can do it? First let's have a look at the DOD directive. In Figure 23-55 DOD says the basis for decision shall never be cost alone, and Figure 23-49 says the idea is to get an "optimum balance between total cost, schedule, and operational effectiveness." This is the same as maximum cost-effectiveness if schedule slippage effects are included in cost-effectiveness.

With this objective in mind, let's discuss some approaches which will help compare contractors for (a) overall program cost-effectiveness, and (b) reliability/maintainability program cost-effectiveness.

5.3 (4.1) BROAD EVALUATION

5.3.1 (4.1.1) Cost-Effectiveness Analysis: If BuShips has asked the contractors for their own cost-effectiveness analyses, then there are three things to evaluate. They are (a) the quality of the analysis, (b) the actual program cost-effectiveness figure they propose to achieve, and (c) the specific reliability/maintainability program cost-effectiveness to the extent we can isolate it. For quality of the analysis these questions may be used:

	Weight	Rating
1. Does the analysis show correct interpretation of requirements?	100	
2. Does it show understanding of the problem?	100	
3. Is the analysis understandable and logical?	100	
4. Is it based on good data, or where not, is it shown that probable data range will not affect conclusions?	100	
5. Are the conclusions logical and correct?	100	
Total	500	

Turning now to the actual program cost-effectiveness arithmetic, Figure 23-56 shows a simple calculation. Let us say that BuShips has specified a performance capability that is normalized to 100%

DOD on PROPOSAL EVALUATION and CONTRACT NEGOTIATION

Directive 3200.9

Participation
VE1a

At no point during the competition shall cost be the sole criterion for decision or selection.

Competition shall be maintained until negotiations for a satisfactory contract for Phase II have progressed, in the judgment of the project manager, to the point at which competition is no longer required.

Contracting for Project Definition Phase
VE3, 8b, F2

The stability of the membership of the contractor structure proposed for PDP and proposed later for Phase II should be a criterion in the evaluation of the Phase II proposals.

Therefore, the negotiations referred to in this paragraph may include negotiations to optimize the final product by incorporation of desirable features from other PDP proposals.

Those recommendations which will result in cost changes exceeding thresholds established by reference (b) shall be formalized by PCP in addition to the memorandum.

COST-EFFECTIVENESS ARITHMETIC

TOTAL PROGRAM		Units	RFP Requirements	RFP Expectation	Recommendation by contractor "A"	Recommendation by contractor "B"
Performance Capability	P	%	100		100	95
AVAILABILITY (and/or Reliability)	A	%	70		80	90
Delivery Effectiveness	D	%	100		95	90
Effectiveness	E = PAD	%	70	70	76	77
Basic Acquisition Cost	C_a	$ Million		20	20	19
Added R/M achievement cost	C_r	$ Million		2	3	6
Resultant Ownership Cost	C_o	$ Million		48	32	16
Total Cost	$C = C_a + C_r + C_o$	$ Million		70	55	41
Cost-Effectiveness	E/C	%/$M		1.0	1.4	1.9

for the stated requirement. That is, 90% performance would mean that capacity, speed, and/or accuracy have been somehow compromised so that system effectiveness is reduced 10%.

Let us say that the BuShips requirement for Availability is 70%, meaning that experience has shown this kind of complex system to be out of commission 30% of the time. And let's say required Schedule Effectiveness is 100%, but in the RFP we have advised the contractors that Effectiveness to the Navy drops 1% for every month of slippage beyond the specified delivery date. Now we can get required and expected system Effectiveness as the product of these three factors, or 70%.

Anticipated Acquisition costs we'll say are $22 million, of which $2 million is expected on the reliability/maintainability programs. And based upon the expected reliability and maintainability behind the 70% Availability, we expect resultant Ownership cost to be about $48 million over the systems useful lifetime. A very modest expectation. Therefore expected Total Cost is the sum, or $70 million. Cost-effectiveness is the ratio of Effectiveness to Total Cost, or 1.0 percent per $ million.

Now let's say contractor "A"s analysis indicated optimum Availability to be 80%, and the extra work to get it would slip schedule by 5 months. But the result would be considerably better Effectiveness of 76%. Moreover the consequent drop of Ownership Cost results in a Cost-Effectiveness improvement of 40% over the requirements. However it would cost an extra $1 million for Acquisition to get that $15 million saving.

Contractor "B"s analysis led him to recommend getting 90% Availability, partly by some sacrifice of Performance Capability to 95%, and by taking 10 months longer for a special stress/strength test program. This nets about the same Effectiveness, 77%, but remarkable reduction of Ownership Cost. The result is a 90% improvement over anticipated Cost-Effectiveness.

5.4 (4.4) EVALUATION SUMMARY MATRIX

When the contractor has been asked to state the cost-effectiveness he will achieve, a much more powerful evaluation is feasible. Figure 23-46 can be expanded as in Figure 23-58.

Down the left side we provide for entries of (a) total program Cost-Effectiveness, because after all this is the true and overriding objective, (b) the reliability/maintainability program Cost-Effectiveness to be explained shortly, and (c) the Confidence

EVALUATION SUMMARY MATRIX

		Units	Requirement Response by contractor			Recommendations by contractor		
			A	B	C	A	B	C
TOTAL PROGRAM								
COST-EFFECTIVENESS		%/$M		1.0		1.4	1.9	
RELIABILITY/MAINTAINABILITY PROGRAM								
COST-EFFECTIVENESS $AD_r / (C_r + C_o)$		%/$M		1.4		2.2	3.7	
CONFIDENCE RATING	Z/A	%		86		71	78	
Availability Expected	A	%		70		80	90	
Delivery Effectiveness	D_r	%		100		95	90	
Contractor R/M Cost	C_r	$Million		2		3	6	
Ownership Lifetime Cost	C_o	$Million		48		32	16	
Program Plan Rating	Z	%		60		57	- 70	

Rating. Again we list some of the key constituents of the figures above, for easy reference.

If we multiply Availability (and/or Reliability) A by the Delivery Effectiveness factor attributable to Availability achievement D_r, we have a number for the Effectiveness contribution resulting from the reliability/maintainability program. Then if we add to the contractors reliability/maintainability program cost C_r the resultant lifetime Ownership Cost directly attributable to reliability/ maintainability achievement (such as maintenance, logistics, failure consequence, etc.) we have the Total Cost to BuShips of program reliability/maintainability or lack thereof. Dividing one by the other we get a Reliability/Maintainability Program Cost-Effectiveness.

For Total Program Cost-Effectiveness we note the example figures developed in section 5.4.1 above. Reliability/Maintainability Program Cost-Effectiveness figures, derived from the same data as explained above, show 1.4, 2.2, and 3.7% per $ million spent. Note the greater leverage compared to the Total Program figures.

In this example, if the 70% truly reflects an excellent and convincing Program Plan, BuShips could undoubtedly decide on contractor "B"s recommended approach. Even if contractor "B" doesn't do as well as everybody expects, the saving of $13 million compared to contractor "A"s proposal leaves a lot of leeway for corrective action as problems crop up.

6. SUMMARY

In this chapter we have reviewed the DOD and CNO directives to achieve a cost-effective optimum reliability and maintainability, and the steps BuShips management and Project Engineers can take to plan and organize such programs.

We have discussed the complete dependency of the reliability and maintainability program upon (a) the basic operational needs and (b), in the future, the cost-effectiveness balance.

In the proposal phase there must be a dialogue between the Bureau and contractors until, by virtue of their estimated cost to achieve various reliability values, the optimum values can be determined. This is followed by detailed planning of the contractor tasks necessary.

Reliability and Maintainability Program Plans, like any contract, must be the sole vehicle of Bureau/contractor reliability and maintainability understanding, and be kept that way as design progresses.

Tasks must be very explicitly stated, particularly describing exactly what output will be produced, who needs it, and who does it. Anythin ' ess produces no worthwhile result.

Proposal evaluation is developed quantitatively, to facilitate fair comparison of contractors proposed plans. But in view of the DOD directives to use cost-effectiveness criteria, suggested approaches are provided. We have modified what has worked ell with a point of departure that, if we try, ought to work. There is no doubt about the soundness of the DOD principles, but implementation will take much patience.

Program Direction can be nothing but fire drills if the Progra planning is incomplete or inadequate. With a solid Program Pl and real understanding between BuShips and the contracto , any good contractor will make BuShips reliability and maintainability Program Direction no problem.

7. R' 'ERENCES

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Chapter 24

PROGRAM CONTROL

Chapter 24

PROGRAM MANAGEMENT

This chapter continues with the broad content of reliability and maintainability programs, with emphasis upon the BuShips management actions necessary to conduct, evaluate, and control such programs to match the requirements. Chapter 23 covered the planning and organizing of such programs.

Unless someone has the clear responsibility for reliability and maintainability management and technical decisions throughout a program, the required results will not be achieved. Ideally it would be very desirable to have a single individual responsible for all reliability and maintainability analysis and decisions on any one program from "womb to tomb" (say from Proposed Technical Approaches to end of system useful life). Let's review the DOD framework and BuShips responsibility structures for (a) RDT&E and (b) shipbuilding programs.

1. RESEARCH AND DEVELOPMENT

Historically, preliminary feasibility studies, systems analyses and advanced development efforts have been steps leading to the initiation of full-scale development of a new weapon or support system. Then, after project approval based upon a Technical Development Plan (TDP), the Departments would prepare a Request for Proposals (RFP). The proposals selected from those submitted led to the negotiation of a contract (almost universally of the cost-plus-fixed-fee type) for an Engineering Development or Operational Systems Development.

Experience over a period of years has shown that these practices have frequently led to "brochuremanship" in proposals, unrealistic technical definition of required system characteristics (including reliability), neglect of the need for further exploratory effort prior to full-scale development, incomplete planning, and overly optimistic contractor proposals which, in turn, have been pursued by the cognizant Department of DOD. These practices have resulted in disruptive or untimely performance or design changes, large cost overruns on development contracts and significant schedule slippages and have degraded the effectiveness of the operational units and escalated the total cost (including production, operation and maintenance).

Further, some projects, which would never have been started if total consequences had been foreseen, have been canceled after partial development, with attendant financial losses. In addition, since the demand for increased funds for the project that was in trouble reduced funds available for other projects, thus bringing about their "starvation" and causing them to be stretched out in time or canceled.

To overcome these problems, a number of new management tools have been used in the last several years -- tools not necessarily new in concept but new in emphasis. Among these are the current OSD Programming System, incentive contracting, PERT and PERT/Cost, Value Engineering, contractor performance evaluation, cost-effectiveness analysis, categorization of research and development (R&D) and the Project Definition Phase (PDP).

Following the encouraging initial applications of PDP, the Director of Defense Research and Engineering (DDR&E) directed the application of PDP to major development projects meeting certain criteria. DOD Directive 3200.9 expanded the application of PDP and provided fundamental direction for the conduct of PDP.

1.1 CONCEPTUAL PHASE 0

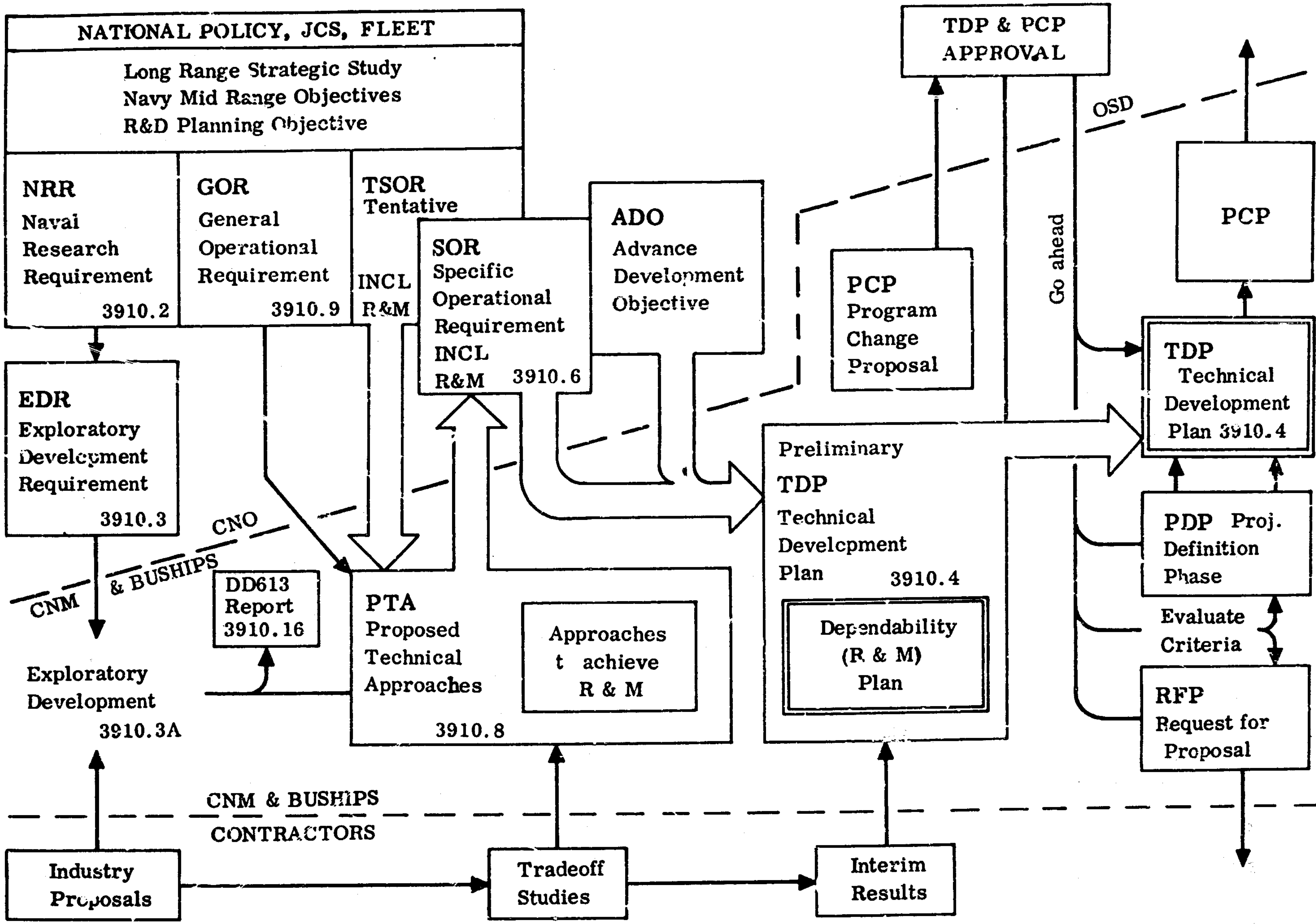
While the application of PDP is not our primary concern here, lack of reliability had much to do with bringing it about. And the underlying principles of PDP can and should be used for all R&D programs. Let us trace, in Figure 24-4, the path of an R&D project from inception.

The Chief of Naval Operations (CNO), cognizant of a need, frames and issues a Naval Research Requirement (NRR), an Exploratory Development Requirement (EDR), or a General Operational Requirement (GOR). Exploratory development progresses, and is reported on a DD613 form to the CNO and to the Director of Defense Research and Engineering (DDR&E).

When CNO has a specific operational problem that requires development, it prepares a Tentative Specific Operational Requirement (TSOR). It is at this point that the tentative <u>reliability, maintainability and/or availability requirements must be expressed</u>, for they will have an impact on the consideration, selection, and treatment of Proposed Technical Approaches (PTA). The PTAs, in turn, must <u>express</u> what reliability, maintainability and availability is achievable by each approach.

PHASE 0 SEQUENCE

OPNAV INST 3900.8C



Independently, NRRs or EDRs cause Exploratory Development, resulting in PTAs which should include approaches to achieve reliability and maintainability. In this case the result is Advance Development Objectives (ADO), which should contain reliability and maintainability needs in the stated quantitative objectives.

Consideration of the PTAs leads to a firm Specific Operational Requirement (SOR), which must include reliability and maintainability figures. From this BuShips prepares a Program Change Proposal (PCP) for Office of the Secretary of Defense (OSD) approval in relation to Five Year Force Structure and Financial Program, and a preliminary Technical Development Plan (TDP).

SECNAV 3900.14A on the Reporting of RD&E Program Information transmits DOD Instruction 3200.6 of 7 June 1962 on the same subject (2). Sections IIIB2a of 3200.6 states that the TDP will include:

> "A narrative statement of the requirements, a brief development plan, and statements delineating the performance, <u>reliability and maintainability</u> characteristics. (See Inclosure 2 for applicable categories and types of reliability and maintainability information to be included.)"

Inclosure 2 of 3200.6, sections A and C, state:

> "TDPs will normally include the kinds of information (listed below). Comprehensive reliability and maintainability programs for feasibility studies, exploratory development and Advanced Development categories are not desired. However, due consideration shall be given to all characteristics, including <u>reliability and maintainability, in the early planning and feasibility study stages</u>, and <u>comprehensive</u> reliability and maintainability programs are expected for <u>operational development</u> projects. It is intended that <u>both the human and hardware</u> aspects of reliability and maintain be considered. The goal is a balanced and integrated effort aimed at <u>optimizing operational effectiveness, total cost and early availability</u>."

> "Normally (Research and Exploratory Development), which are essentially the requirements, will be precisely and quantitatively stated. Information in the TDP responsive to Advanced Developments and Engineering Developments should outline the <u>plans for achieving reliability and maintainability</u>, including the significant elements. In some cases, listing of a significant element without detail is satisfactory. For

example, indication that reliability apportionment and prediction is a part of the reliability program may be sufficient. In other cases, for example, reliability test and demonstration, and principal details of the planned program are necessary. Whenever there is heavy emphasis or unusual treatment of an element, this should, of course, be detailed."

Accordingly the TDP must include a reliability and maintainability Program Plan, as shown in section 3. of chapter 23. The PCP and preliminary TDP are routed to OSD for PCP approval and go-ahead, which authorizes preparation of a firm TDP (and revised PCP if needed), a PDP Plan (if used), a Request for Proposal (RFP), and preparation of evaluation criteria. Content of the RFP, so far as reliability and maintainability are concerned, is covered by section 2.1 of chapter 23.

1.2 DEFINITION PHASE I

If PDP is used, Figure 24-7 shows the proposals resulting from the above RFP, and proposal evaluation is described in section 4. of chapter 23. Contract negotiation is discussed in section 4. herein. In this case the contract results as in Figure 24-8, in proposals for Phase II full-scale design, development and production, and these proposals in turn can be evaluated as in section 4. of chapter 23. After the necessary refinement of the TDP (including its Dependability Plan) and PCP, and dual negotiation, a final ACQUISITION Phase II contract is negotiated.

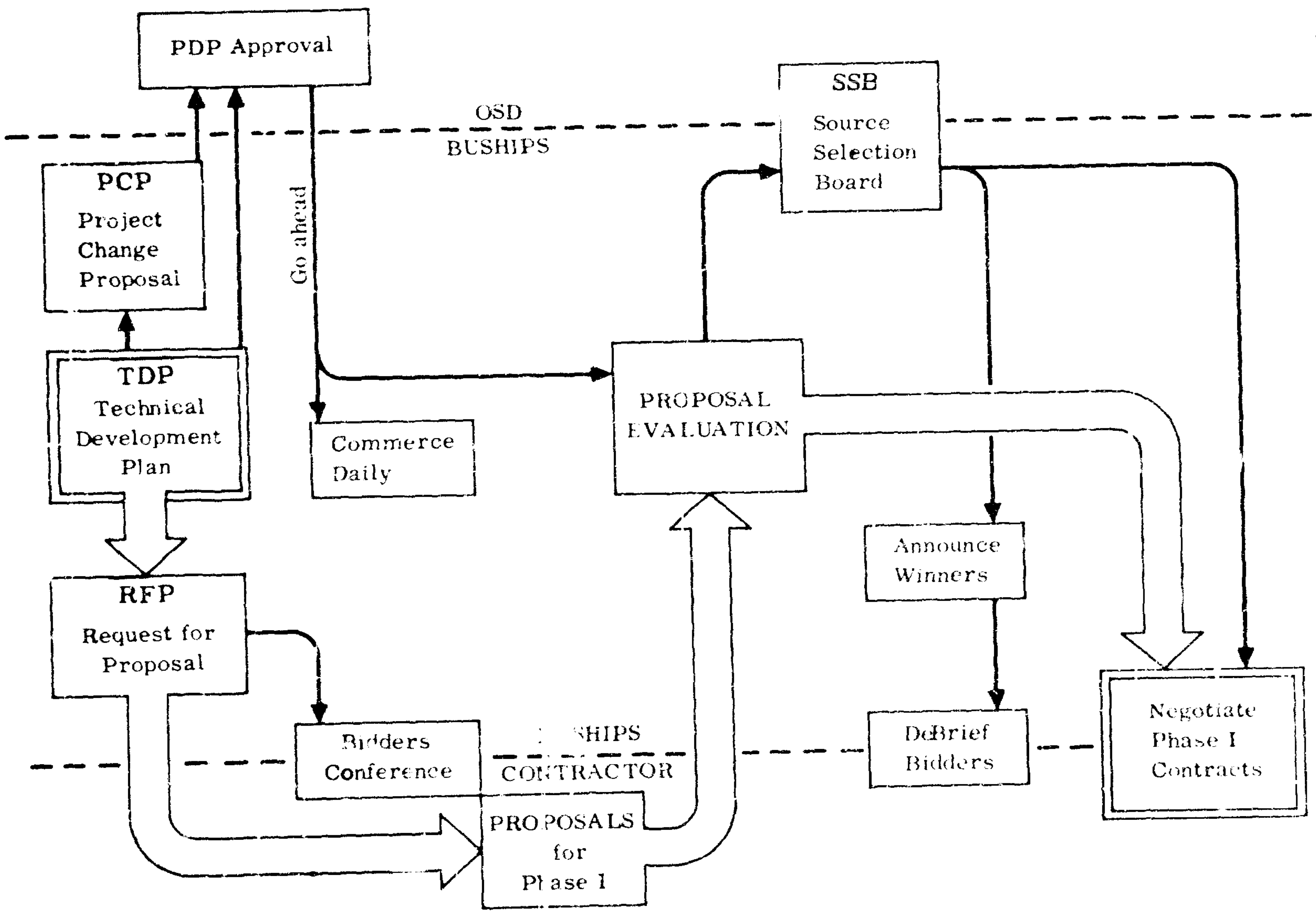
If PDP is not used, the procedure is identical except that the steps between the Proposals for Phase I block (Figure 24-7) and the Proposals for Phase II block (Figure 24-8) are omitted.

1.3 R&D MANAGEMENT

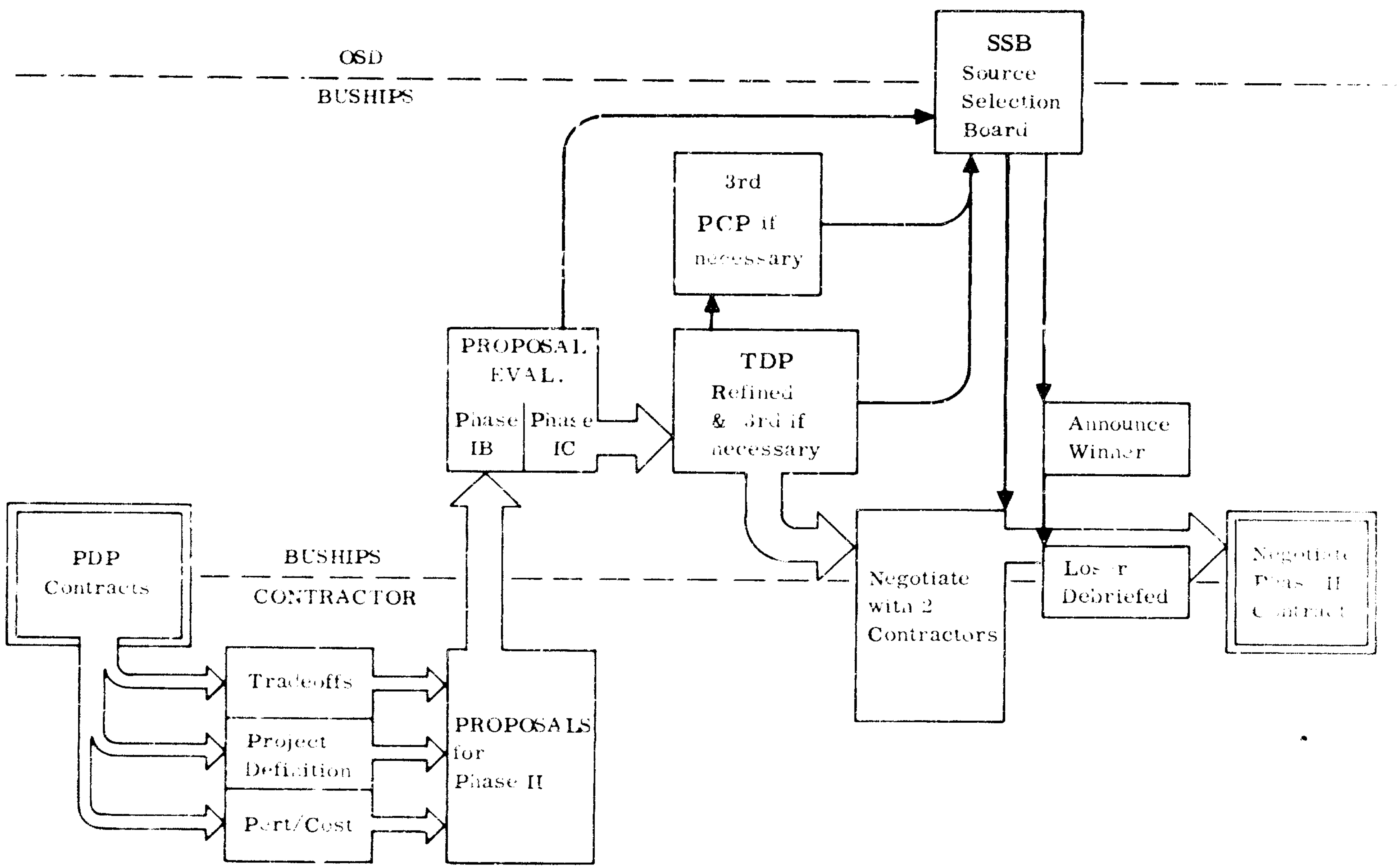
For BuShips management and execution of the Research, Development, Test and Evaluation Program, Figures 27-9 and 24-10 from reference (1) show very concisely the distribution between Program Manager and Technical code responsibilities. In concept the Program Manager is responsible for determining what is to be done to meet Bureau requirements, and the Technical Code is responsible for determining how to execute the selected tasks within the time-cost-performance framework.

Clearly it is the job of the Project Engineer in the Technical Code to (a) determine how to achieve the required reliability and maintainability, to (b) recommend which tasks are acceptable, (c) determine method of accomplishment, (d) prepare Proposed

PHASE IA SEQUENCE



PHASE IB & IC SEQUENCE



BUSHIPS RDT&E RESPONSIBILITIES

BuShips 5430.41A, 3 May 1963

PROGRAM MANAGER CODE	TECHNICAL CODE
Initiate tasks	Initiate tasks Appraise technical task feasibility
Decide which tasks acceptable	Recommend which tasks acceptable
Decide which tasks to fund	Recommend which tasks to fund
Decide which tasks to be done by BuShips Decide which tasks to be done elsewhere	
Liaison with other Bureaus	Liaison with other Bureaus
	Determine method of accomplishment
Approve task reports	Prepare task report 330. Coordinate task reports
Review long-range objectives Coordinate review of GORs	
Review R&D long-range plans	315: Prepare R&D Long Range Plans
Prepare RDT&E Project Cards Approve PTAs	Prepare PTAs
Prepare TDPs	
Initiate manpower requirements Review & concur with non-RDT&E funding	
Plan, prepare & defend budgets Liaison with OPNAV, ASN(R&D), DDR&E, DCA, DASA, DIA, etc.	336: Accounting for RDT&E funds

BUSHIPS RDT&E RESPONSIBILITIES

BuShips 5430.41A, 3 May 1963

PROGRAM MANAGER CODE	TECHNICAL CODE
	Prepare project plans for Technical Evaluation Provide technical direction for Technical Eval. 330B: Coordinate Tech Eval with OPNAV, OPTEVFOR
Approve unsolicated proposal action	333: Unsolicated proposal control 333: R&D requirements to industry Contact point for contractors Evaluate unsolicated proposals and action
Approve Procurement Requests	Prepare specifications Prepare bidders list Prepare Procurement Requests (RFP) 330: Authorize Procurement Requests funding Justify sole source procurement Pre-award conferences Recommend award to code 1700 Provide facilities justification
Decide to reprogram funds Approve contract change of scope	Recommend contract termination Technical contract administration Initiate contract change of scope Arrange technical presentations
Progress obligation rate	
Approve laboratory task assignments (/320) Review laboratory task reports	320: Coordinate formulation of laboratory program 320: Approve laboratory technical program Initiate laboratory task assignments 320: Designate lead laboratories Technical guidance to lead laboratory Review laboratory task reports

Technical Approaches accounting for reliability and maintainability, specifications and RFPs to achieve required values, (e) administer the technical contract, and (f) initiate any required changes of specified reliability and maintainability.

The Technical Codes, whether or not PDP is used, are responsible for hardware design and evaluate activities, and responsible for making certain that reliability and maintainability requirements are invariably considered and specified in hardware PTAs, TDPs, and RFPs, evaluate the resulting proposals for reliability and maintainability content, recommend awards, participate in contract negotiation of reliability and maintainability content, and administer contractor reliability and maintainability performance.

For example in preparing PTAs, the Technical Code may have evaluated one or more unsolicited proposals in the same area, noting the reliability and maintainability these contractors expected to be able to achieve. He must insure that the probable reliability effects of departures from existing designs are evaluated, that likely reliability problem areas are identified (e.g., perhaps microcircuitry is involved, and thermal sensitivity of the semi-conductors is known to be causing serious problems in such circuitry; the PTA should indicate how this would affect system reliability and what approach would be used to minimize adverse effect).

In preparing a Technical Development Plan, he includes a Dependability Plan that is firmly based on mission requirements and system performance parameters. He must assure himself that the plan provides for resolving the problems of interface with other shipboard systems and that it identifies any areas which will require special reliability upgrading effort. If underwater pickup resistance to corrosion must be improved by an order of magnitude, he must be sure that the Dependability Plan provides for such effort, that it shows the type of testing required to verify this new resistance, and that cost and schedule implications are clearly indicated. He must also insure that the remaining sections of the TDP reflect this requirement. The engineering plan must contain provisions for appropriate development, the schedule must allow for it, the cost must be included in the overall cost breakdown, etc.

2. SHIPBUILDING PROGRAM

As detailed in OPNAV 4700.12B, the "development of ship characteristics and authoritative cost estimates is a complex and lengthy procedure, requiring inputs from the Fleet, different sources within OPNAV, cognizant technical bureaus and the Bureau of Naval Personnel. Basic guidance is provided by Mission and Tasks as approved by the Chief of Naval Operations. The infor- contained in the Mission and Tasks is amplified by single page characteristics which are prepared by the type sponsor, approved by the Deputy Chief of Naval Operations (Fleet Operations and Readiness) and provided to the Chairman, Ship Characteristics Board. These single page characteristics delineate the significant features and capabilities which form the basis of cost and feasibility studies by the Chief, Bureau of Ships, and the resultant development of the initial credible price estimate. Based on the above information and guidance, approved ship characteristics are developed.

"The statement of Mission and Tasks for each type of U.S. Naval ship provides the key to a ship's ultimate capabilities, characteristics and cost. Because it furnishes a broad statement of the purpose for which the ship is to be designed and the tasks which the ship can be expected to accomplish, each word used in the Mission and Tasks statement is significant. The stipulation of an excessive capability in either the mission or tasks may well result in an overly complex ship priced at a cost which jeopardizes actual construction. Similarly, understatement of capability could result in a ship of less-than-desirable operational qualities."

2.1 MISSIONS AND TASKS

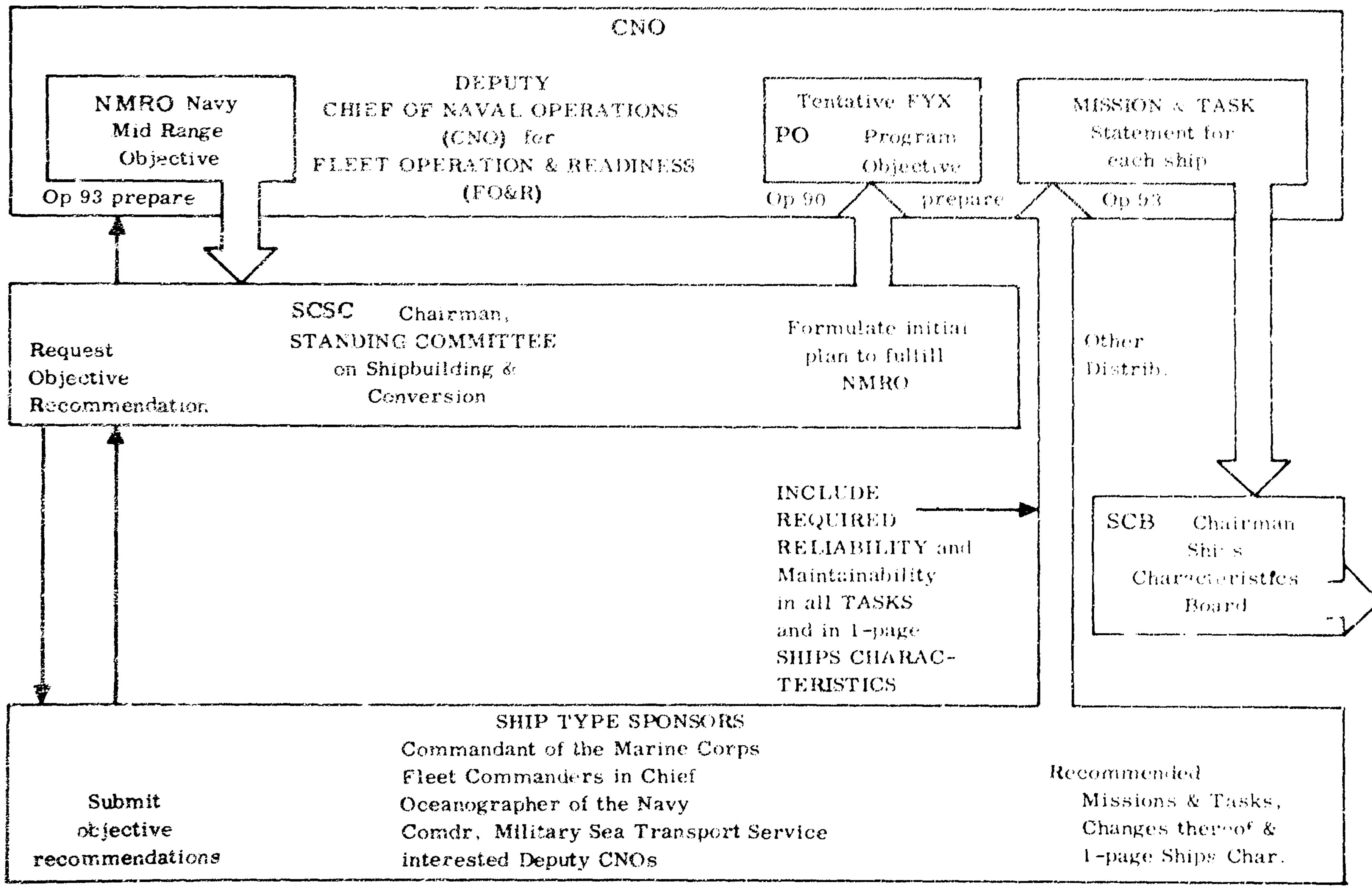
Figure 24-13 shows the sequence leading up to transmission of the Mission and Task statement for each ship to the Chairman of the Ships Characteristic Board.

The reliability and maintainability requirements are not being included in the recommended Tasks, nor in the 1-page Ships Characteristics, today. But the incorporation of such requirements, where applicable, will utlimately avoid or minimize many problems such as (a) excessive system "out of commission" time, (b) degraded weapon system effectiveness, (c) impractical maintenance manpower and skill requirements, and (d) pre-emption of new weapon system funds to pay for the maintenance.

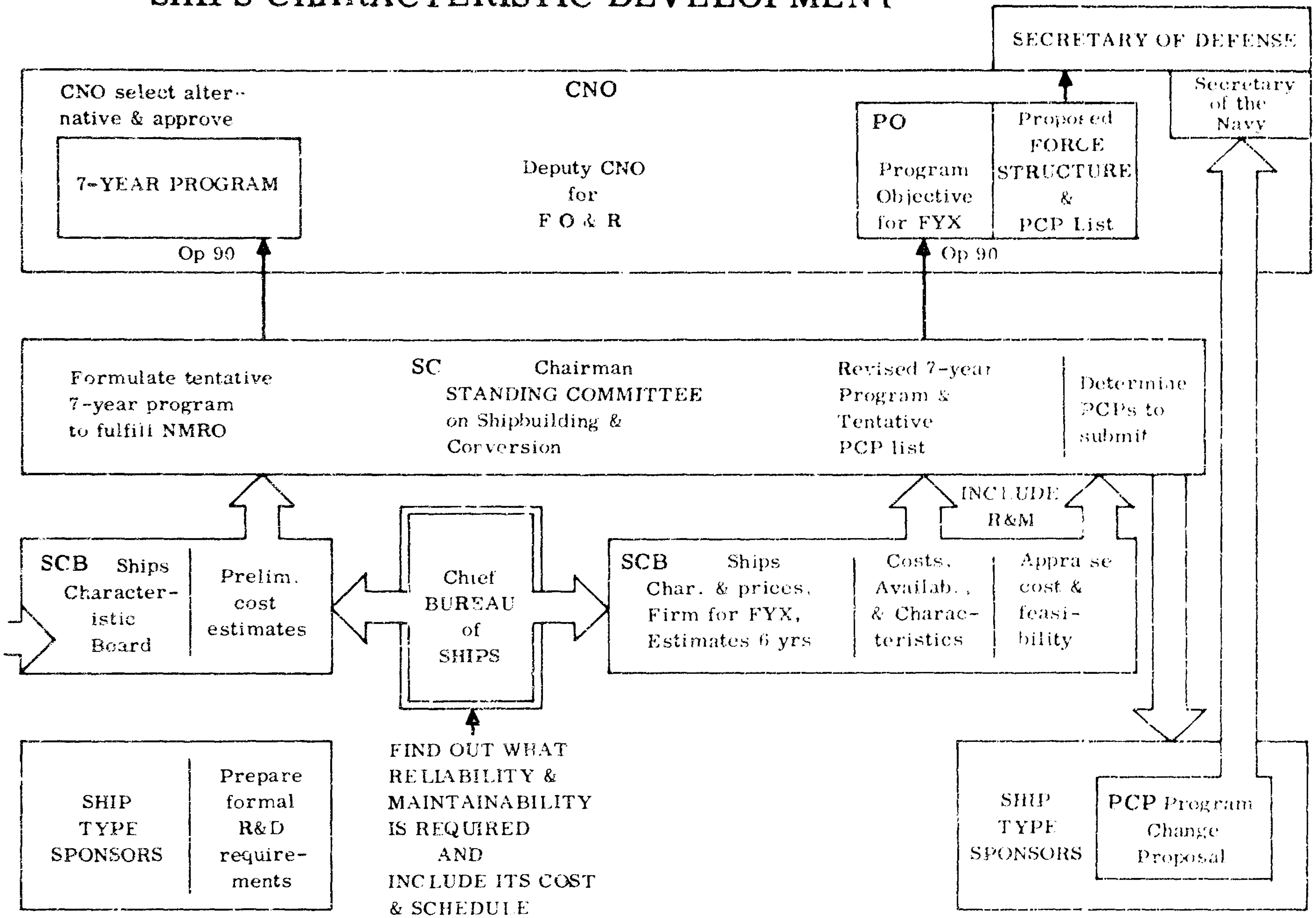
2.2 SHIPS CHARACTERISTICS

Figure 24-14 shows the next sequence leading to final PCP approval by the Secretary of Defense. BuShips primary point of contact, for ships characteristics and cost, is with the Ships Characteristic Board (SCB), but BuShips is not considering their feasibility or

MISSION AND TASK DEVELOPMENT



SHIPS CHARACTERISTIC DEVELOPMENT



cost. It would appear that BuShips can help avoid those future fleet and budget problems by finding out from SCB how much reliability and maintainability is needed, and including its cost and its schedule impact.

2.3 SHIPBUILDING MANAGEMENT

Referring to Figure 24-16, the Ships Characteristics Board (SCB), in response to the Mission and Task statement issued by the Chief of Naval Operations (CNO), delineates the desired characteristics to the BuShips Ships Design Division. Although such desired characteristics do not yet include the reliability and maintainability characteristics desired, they should be included as rapidly as feasible.

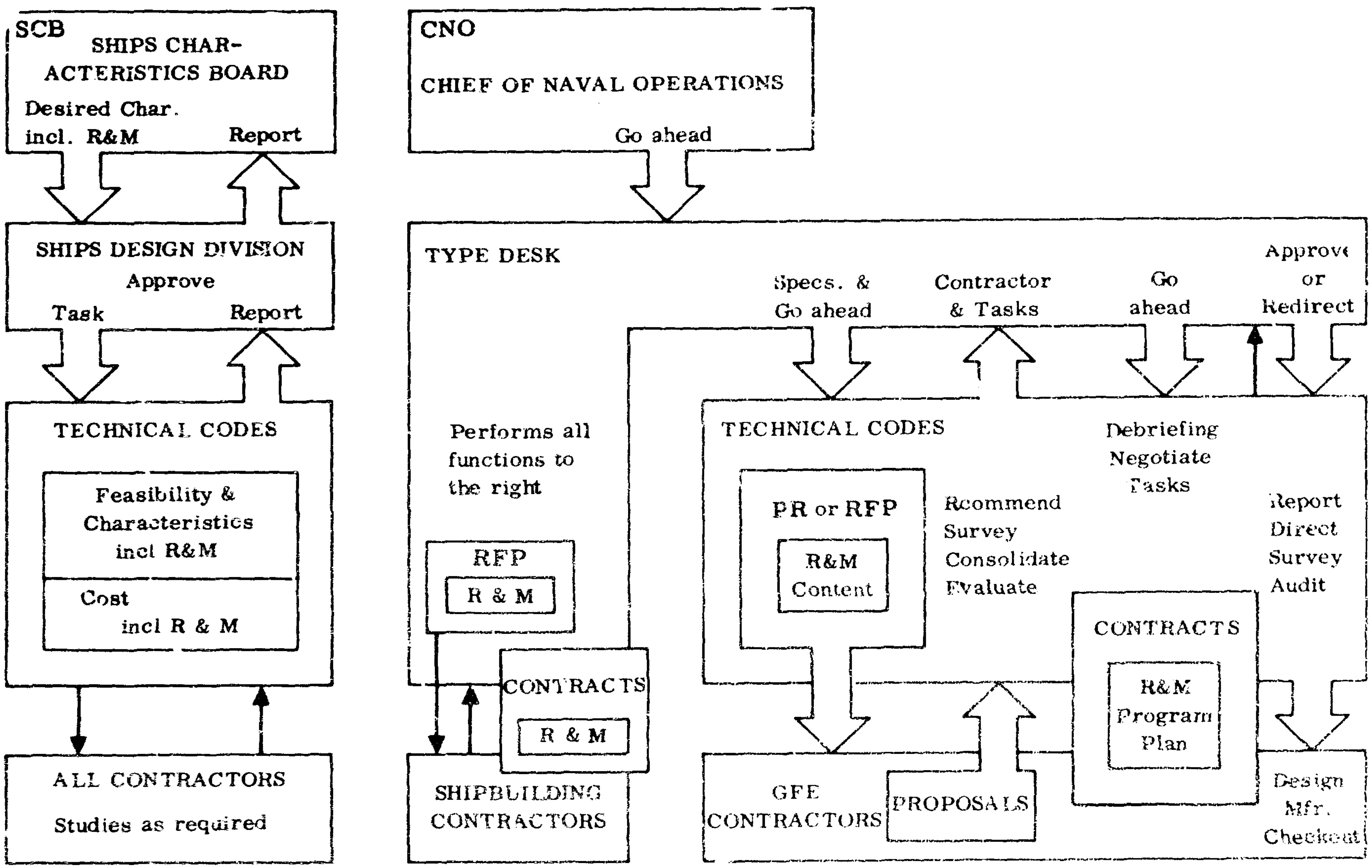
The Ships Design Division, like the Program Manager Code for RDT&E, delineates the task of determining feasibility, characteristics and cost, to be executed by the cognizant Technical Code. The Technical Code may need some help from one or more contractors, for which contracts are placed. The resulting report of feasibility, characteristics and cost should include the reliability and maintainability characteristics and cost. It is then transmitted back to SCB via the Ships Design Division.

After the SCB has made final recommendations to the Standing Committee (Figure 24-14) and the program is approved by the Secretary of Defense, CNO issues authorization to the BuShips Type Desk to proceed with acquisition. The Type Desk integrates the entire program. For shipbuilding and conversion it deals directly with the contractors, including preparation and issuance of RFPs which should include any reliability and maintainability requirements. When contractors proposals are received the Type Desk selects a contractor and negotiates a contract, which should include any reliability and maintainability requirements.

For GFE equipment the Type Desk, again like the Program Manager Code for RDT&E, authorizes the Technical Code to prepare and issue final P.R. or Requests for Proposal, the reliability and maintainability content of which should be as in chapter 23.

The contractors offer their proposals, which the Technical Code evaluates, consolidates the best features of all, may survey one or two bidders, and makes its final recommendation to the Type Desk. After its decision the Technical Code debriefs the losers and proceeds with contract negotiation. The contract should contain a reliability and maintainability Program Plan as detailed in chapter 23.

SHIPBUILDING R&M RESPONSIBILITIES



Throughout performance of the contract the Supervisor of Shipbuilding (SupShip) or local cognizant government representative audits contractor performance, which should specifically include reliability and maintainability progress. He should conduct periodic surveys of contractor reliability and maintainability capability. He directs the contractor, and reports progress to the Type Desk. The Type Desk of course must approve or redirect the Supervisors actions as necessary.

Having discussed the RDT&E and Shipbuilding workflow, we can turn our attention to some methods found effective in industry.

3. INTERNAL RESPONSIBILITY ASSIGNMENT

While the above BuShips allocation of responsibility says that some code is responsible for reliability and maintainability at all times, that will not get the job done within the respective codes. The cliché "Reliability is everybodys business" means that nobody feels personally responsible to do much about it, except, perhaps, to give lip service.

So it is extremely important that every code management issue and enforce internal instructions that (a) name an individual specifically responsible for reliability and maintainability on every program (one may handle several programs), (b) cause the named individuals to get educated on this subject, and (c) require them to know program reliability and maintainability status at all times. We are not suggesting additional manpower. We are suggesting that every affected Code should train say 10% of its people to become real reliability and maintainability experts.

This is particularly important in SupShip and InsMat offices cognizant over contractors plants, where he can get close to the contractor counterparts and understand the problems.

4. CONTRACT NEGOTIATION

See chapter 23 section 2.4. Normally the BuShips financial contract negotiator and the Project Engineer will not be sufficiently expert on detailed reliability and maintainability problems and impact to judge consequent contractual content. Therefore it is imperative that at least one BuShips reliability/maintainability specialist participate in the reliability and maintainability Program Plan and incentive (if used) negotiation. And it is just as imperative, for the same reason, that at least one contractor reliability/maintainability group supervisor participate.

The BuShips reliability/maintainability specialist should recommend (a) exact final wording of the Requirements, including the exact means of verification of their achievement, (b) exact content of the Program Charts, (c) exact content of all Task Delineation and should (d) participate in negotiation and approval of the proposed reliability/maintainability organization. He should (e) recommend and concur with the incentive relationship to cost-effectiveness so far as reliability and maintainability are concerned. He must not concur with a relationship which fails to compensate the contractor for reliability/maintainability expenditures that will clearly improve cost-effectiveness.

5. CONTRACTOR EVALUATION

This section is concerned with the evaluation of a contractor's capability to achieve required reliability and maintainability, as well as evaluation of his actual achievement during the contract.

5.1 PRE-AWARD SURVEYS

Prior to contract award there should be a comprehensive survey of the reliability and maintainability competence of the one or two contractors still under consideration. At this point the Proposal Evaluation questions of chapter 23 can be used directly, except for the few as outlined in Figure 23-18, that may not be applicable. Much more detailed surveys (1) may be used if warranted, but they are costly and time-consuming.

In order to provide uniformity of assessment across all contractors, Technical code 609 is responsible for all BuShips surveys of contractors reliability and maintainability competence. Upon request, code 609 will execute this standard sequence:

1. Schedule surveys.
2. Assign a survey chairman (INM or SupShips)
3. Notify the contractor and cognizant INM or BuShips personnel by letter at least 30 days prior to the proposed survey.
4. Conduct a pre-survey conference of the team with contractor personnel.
5. Conduct the survey and evaluate the program against the pertinent items of section 5.0.

6. Conduct a post-survey critique for the contractor and obtain contractor response.
7. Prepare a final report to the requesting Technical Code, copies to team members.
8. Follow up with the contractor to determine corrective action taken.
9. Maintain records of all surveys.

The survey team will consist of the INM or SupShips chairman, a representative of the cognizant Bureau Engineering group, a representative of code 609, and one or more specialists as may be required for the primary nature of the contractors design reliability problems. It is extremely important that contractor design reliability and analysis capability be surveyed by experienced engineers. Industry experience is that "QC" surveys cannot evaluate reliability and maintainability. Person-to-person evaluation of technical competence is far more important than checking documents, although the latter is necessary.

5.2 MONTHLY REPORTS

The regular monthly contractor reports in chapter 22 section 12. serve as a basis for monthly BuShips evaluation of reliability and maintainability (a) requirements, (b) predictions vs. apportionment, (c) task progress vs. schedule, and (d) verification results. These must be thoroughly digested by the cognizant INM or SupShips reliability and maintainability specialist, discussing any questionable items with the contractors reliability and maintainability specialist. Then for RDT&E programs he can prepare the reliability section of the Monthly Project Evaluation (MPE) and OPNAVINST 3910.15 Quarterly Project Reliability Summary Sheet covered by BuShips Instruction 3900.27, which are then evaluated semi-annually in accordance with BuShips R&D memorandum 8-64 and DOD Instruction 3200.6.

5.3 RELIABILITY GROWTH

It would be very unrealistic to expect any contractor to achieve the predicted values in the initial design. Predictions are based upon more or less mature designs. In the iterative process of locating potential problem areas and minimizing their effects or eliminating them, inherent reliability improves. Historically, predicted reliability increases during the design phase and can be projected forward to operational use. As test data becomes available, predictions have more validity. Problems invariably show up in the hardware that could not be forseen in the design, and achieved reliability is significantly lower than that inherent.

Aggressive corrective action eliminates these problems as the program progresses, and achieved reliability increases.

Analysis of reliability growth in the aerospace industry shows reasonable consistency between programs, depending on the degree of urgency and its effect on ability to implement corrective action when problems are uncovered in the hardware phase. These rates of growth are roughly equivalent to doubling the MTBF in 4 years, and should be applicable as approximations to ships GFE programs. Cognizant Navy managers should be alert to any significant failure of such growth to materialize in their programs.

5.4 POST-AWARD SURVEYS

In order to detect trends and assure compliance with reliability and maintainability requirements, INM or SupShips should conduct regular surveys of each contractor every 6 to 12 months, covering all BuShips contracts he has at each survey. Again the chapter 23 Proposal Evaluation can be used, though it is possible that the excellent but very detailed NASA Reliability Program Evaluation Procedures (2) will be adopted by DOD as the government standard. However the Procedures (a) do not cover several of the very important chapter 23 areas, (b) assume a particular assignment of organizational responsibilities that many contractors may find incompatible and uneconomic, (c) contain 25 to 50% redundancy for cross-checking, and (d) seem very expensive to conduct, and keep reasonably current, for the utility obtained. Undoubtedly further refinement of it can be expected.

If conducted every 6 months on each contractor, using the same chapter 23 weights, trends will be evident. If the same rating system is used across all contractors, the carefully-used results can highly motivate a contractor to correct deficiencies.

6. CONTROL

Every effort should be made to encourage the contractor to control the program himself, basing his decisions or recommendations on analyses which are in turn based upon the BuShips cost-effectiveness criteria. Then BuShips need only watch and regularly evaluate the program.

Often there will be changes in BuShips planning, such as an added mission for a higher-level system that this program supports. Such changes can easily change the program cost-effectiveness criteria, and the contractor should be immediately so informed.

Then the contractor can analyse the new situation and make recommendations for contract change, if any.

But then there are inevitably contractor deficiencies in achievement of requirements, achievement of tasks, schedule adherence, or excessive expenditure. It is then up to the SupShips and/or the Technical Code to (a) get the facts, and thoroughly understand the problem, (b) require an official commitment from the contractor or corrective action by a specified date, or (c) recommend BuShips adjustment of the Program Plan or contract to fit the unforeseen contingency.

Both technical and management capability are vital to a contractors ability to satisfy reliability requirements within budget and schedule constraints. The better the technical capability the contractor has, the less his attention is absorbed by the question, "How can I make this system do the things it should?" And the more it can be devoted to answering the other question, "How can I best assure that this system will not fail?" Evaluation of his ability to meet reliability requirements, therefore, involves not only his understanding of organization for reliability and maintainability control, but his overall technical background and management history.

Two great obstacles to reliability achievement are: (a) inability to stay on schedule, and (b) poor internal communication. As any part of the schedule begins to slip, pressure mounts rapidly to make do with whatever shortcuts are available. The first work to suffer is the review and double-checking type, with the result that errors are not detected. At the same time, the work is done more hastily, so that decisions are not weighed as carefully and errors become more likely. By the same token poor internal communication increases the probability of hardware interface problems, poorly-coordinated problem solutions, and misunderstood requirements.

7. SURVEILLANCE

InsMat and SupShips are responsible for direct surveillance of contractor performance, and therefore of implementation of contractor reliability and maintainability programs. Their resident people will make many tradeoff decisions on problems, within their authorized scope, that never need to get to Washington. Decision by those closest to the problem is a tenet of good management. There is no substitute for close contact with the contractors.

There should be a local InsMat or SupShips reliability/maintainability specialist who receives all such contractor reports, and should get them for prior informal review to give the contractor an opportunity to correct deficiencies. He should require monthly contractor meetings at which unresolved reliability and maintainability problems are discussed and action assignments made.

But beyond formal meetings, he should be continuously visiting appropriate groups to learn how things are being done and to understand the problems. He should be constantly alert to opportunities where he can help the contractor, perhaps by getting information from BuShips or other sources.

7.1 MATERIAL INSPECTION SERVICE

Monitoring of progress, inspection and many of the tasks of contract administration are performed by the Material Inspection Service (MIS), including but not limited to Inspectors of Naval Material (INSMAT) and Supervisors of Shipbuilding.

7.2 INSPECTORS OF NAVAL MATERIAL

INSMAT offices are located in large cities and near major industries. They work directly for the Office of Naval Material and have prime cognizance over source inspection of material, preaward and other surveys of contractors plants, and proper use of government furnished material and facilities. A high level of competence is to be expected on inspection and acceptance tasks and administrative duties. Transmittal of the contract to the local office cognizant over the plant is all that is required to obtain their services to the extent defined in the contract and specifications. This means all unusual inspection/acceptance functions must be spelled out to insure their accomplishment.

A high level of engineering and analytical competence is not to be expected, although it may occasionally be available. For unusual or analytical tasks that might be considered within the capabilities of a top grade inspector, a letter should be written to the cognizant office outlining in comprehensive detail the duties desired.

Where no cognizant INSMAT is assigned over the plant, cross servicing by Air Force or Army inspectors may be arranged.

7.3 SUPERVISORS OF SHIPBUILDING

Supervisors of Shipbuilding (SupShips) are BuShips Inspection

Offices assigned cognizance over Shipbuilding and boat building contracts. They are physically located near the shipyard and have the duties of contract administration over the details of the contract. They have delegated contracting authority for the negotiation of costs incident to changes authorized by the Bureau, they progress the work, enforce contract requirements, and review contractors drawings and procurement. They are staffed with Inspection, Engineering and Financial personnel with a high level of technical competence. At the present time there is no particular capability in analytical reliability.

Where special reliability analytical or monitoring tasks are involved at the contractors plant, or in procurement of contractor furnished material, detailed instructions should be provided by letter.

7.4 MATERIAL INSPECTION SERVICE UTILIZATION

Where reliability requirements are included in the contracts, the cognizant office of the MIS should be briefed, preferably by letter, of the limitations of their authority. Such actions as approval of contract changes, approval of use of non-standard parts, and qualification by similarity should be specifically assigned or specifically reserved to the Bureau.

8. SUMMARY

In this chapter we have outlined the broad management of reliability and maintainability programs, with emphasis on the conduct, evaluation, and control of such programs. Control decisions are made by the Program Manager of RDT&E programs, and by the Ships Design Division or the Type Desk for the Shipbuilding and Conversion program.

Detailed programs are developed by the Technical Codes for the above approval and decisions, and likewise Technical Code contract evaluation and control is subject to the above approval and decisions. Thus this chapter attempts to describe the interface flow of work for reliability and maintainability programs.

We have tried to emphasize that not much will happen until some specific personnel are told that they "are henceforth the reliability and maintainability experts," that they should "get educated" on the subject, and then that they are responsible for specific contract reliability and maintainability achievement.

We have tried to emphasize that contract negotiation involving reliability and maintainability incentives cannot be done apart from thorough knowledge of reliability and maintainability feasibility, tasks and consequences.

We have tried to emphasize that contractor evaluation requires technical person-to-person understanding of the problems, so that the monthly reports have significance.

But above all, if the program is thoroughly conceived, with insistence upon mutually understood Program Plan language, then it really takes a minimum of control to get good results.

9. REFERENCES

1. Management and Execution of the Research, Development, Test and Evaluation Program; responsibilities for, 3 May 1963, BuShips Instruction 5430.41A.

2. Reliability Program Evaluation Standards, NASA SP-6002, September 1963, National Aernautics & Space Administration, Washington, D. C.

Chapter 25

SYSTEM EFFECTIVENESS

Chapter 25

SYSTEM EFFECTIVENESS

Admiral Schoech recently stated (1):

> "System effectiveness, and its fiscal corrollary cost effectiveness constitute the most important concern of military R&D management."

System effectiveness concerns the capability of a system to perform its intended function. DOD Instruction 3200.9 states

> "Trade-offs shall be used to obtain, within the mission and performance envelopes, an optimum balance between total cost, schedule and operational effectiveness for the system."

The reasoning behind these statements is based on high cost penalties, both direct and indirect which are associated with low reliability. Some of the direct costs are

- additional systems that are required to carry out a given mission
- additional spares used in support of the systems
- added operating bases, supply and maintenance points, tenders, and test equipment
- additional maintenance workload caused by frequent failures
- additional technical training for maintenance personnel.

Some indirect causes related to unreliability which are difficult to assess in terms of cost are

- loss of prestige due to failure of system
- loss of ship's effectiveness
- false security which jeopardizes America's defense posture.

One of the most costly items attributable to unreliability is the maintenance and support costs of systems. Maintenance expenditures in the DOD account for more than 25 percent of the defense budget. In FY61, 960,000 people (approximately) were directly concerned with maintenance. The figures quoted are believed to have grown correspondingly with the defense budgets. More information on the cost of unreliability is contained in chapter 26.

1. THE BASIS OF SYSTEM EFFECTIVENESS

The System Effectiveness concept is derived from the system engineering process. It recognizes the interaction and interdependence of the many system parameters and seeks to optimize them rationally in the interest of overall system accomplishment. The concept commences with identification of an operational requirement. Ensuing efforts are directed toward satisfying that requirement.

The selection of systems to develop and the selections of contractors to develop them must be in conformance with National Strategic Objectives and must include due consideration of economic factors in their acquisition and ownership. That is they must be effective in performing their function and must make most efficient use of the budget.

Reliability and Maintainability must be designed into equipment at the system level, and subjected to design and operational trade-off analyses with weight, size, cost, delivery, etc. Optimum system effectiveness can only result through this judicious weighing of each of the system characteristics.

1.1 APPLICATION

While it is apparent that this concept is clearly applicable to new development programs, its use is not limited thereto. It may be applied equally well to the Bureau's problem of improving existing systems. As with R&D programs, the concept is introduced when operational factors are identified. The essential difference is that the concept can be tailored to specific conditions of change when:

- a previous operational requirement has been modified, or

- available equipment fails to meet an existing operational requirement or

- system improvement is desired to improve its cost-effectiveness.

The System Effectiveness concept is not restricted by the development nature of a system. Its use, however, should be justified on the basis of its economy in achieving the desired improvement. Determinants may well be the degree of improvement sought versus constraints of time and/or cost.

1.2 CRITERIA FOR SYSTEM EFFECTIVENESS

The ultimate output of any system is the performance of a set of intended functions. They may be described by some system output characteristic such as satisfactory message transmission in a communication system, or positive identification in a shipboard radar system.

The system engineering approach views the ship itself as a platform. Although it has specific functions, it is dependent upon the individual functions of its primary systems to propel, navigate, steer (submerge for submarines). The function of the platform (ship) may be to carry weapons or detection systems with their necessary controls and support, or to provide logistic support. These systems require secondary or support systems such as personnel, communications (internal and external), power, and casualty control.

Each system has a mission (or missions) related to either the mobility and positioning of the ship, the weapons or detection equipment, or support of the ship's personnel.

Mission Requirements: Through proper evaluation of the system's purpose, it is possible to establish mission duration requirements for each type of ship mission. Three standard mission cycles in use are:

1. Time between shipyard overhauls - 4 years.

2. Overseas tour of duty, including transit time - 3 months. For submarines, submerged period may be three months.

3. General Quarters (battle stations)- 4 hours.

Levels of Importance: Systems may be classified as to their relative importance for each of the three cycles. Fire Control, weapons, power, casualty control, propulsion, steering, etc., must have a very high Reliability for General Quarters. However, for a three-months tour, their essentiality will vary. Propulsion must have a high Availability, steering a high Reliability, while fire control may have no other requirement than stand-by readiness. Search equipment may require a high Availability. Each system must be evaluated against its requirements, including requirements to support other systems in order to establish meaningful essentiality levels.

Capability of Restoration: The capability of self maintenance of ships does in fact have limits. The limitations are:

1. skills of personnel
2. availability of personnel
3. spare parts and materials
4. operational constraints
5. equipment and facilities
6. access.

Summary: The term System Effectiveness is used to describe the overall accomplishment or worth of a system. It relates to that property of system output which is the reason for its existence - namely, the carrying out of some intended function. The System Effectiveness concept realistically considers

1. system function
2. system mission duration requirements based on stated cycles and logistics capability
3. levels of system importance
4. capability of restoration.

If the system is effective, it will carry out its function for the duration under actual conditions. If it is not effective, attention must be given to the system parameters which are deficient.

2. SYSTEM EFFECTIVENESS FACTORS

System Effectiveness is the combination of many factors, each in some way contributing to the capability of the system to perform its intended function. Some of these are:

A. Performance Capability

1. Technical Capability

a. Capacity (load, range, etc.)
b. Speed (knots, microseconds, etc.)
c. Accuracy (bearing, resolution, etc.)
d. Invulnerability to countermeasures

2. Possible Limitations Upon Performance

   a. Space and weight requirements
   b. Input power requirements
   c. Input information requirements
   d. Requirements for special protection against shock, radiation, vibration, high pressure, and other environmental influences

B. Dependability

1. Reliability

   a. Failure-free operation
   b. Redundancy or provisions for alternate modes of operation

2. Maintainability

   a. Time to restore failed systems to satisfactory operating status
   b. Technical skills required for maintenance
   c. Effects of use upon maintenance

3. Logistic Supportability

   a. Spares availability
   b. Test equipment and facilities

C. Procurability

1. Acquisition Cost

2. Development Time

2.1 PERFORMANCE CAPABILITY

The reason for the existence of the ship is the performance of an intended function. With the large number of possible requirements that may be operationally imposed on a ship, the equipment installed can not always be matched to the requirements. A radar operating within specifications may not be able to detect a surface target at the extreme of its range (due to heavy weather), or it may not be able to detect a target beyond the limit of its range (we might call this mis-application). Or the requirement may not utilize the full capability of the equipment, as a twenty-five megaton bomb greatly overkilling a target.

To start to evaluate the effectiveness of an equipment for a particular function or "mission", the first need is a figure of merit for the proposed (or each proposed) system that describes the limit of its capability. Many such figures of merit can be envisioned. For a supply ship, to take a simple case, such a figure of merit could be the ton-miles of stores it could haul, the ton being based on full capacity loading and the miles on maximum cruising radius without refueling. This figure of merit we call Performance Capability.

For a specific mission this capability may or may not be adequate. Where it is not, the system cannot be considered for that particular mission. Comparisons of excess capability, where the proposed system is more than adequate, become an area of trade-off with cost, delivery schedule and other factors.

2.2 DELIVERY EFFECTIVENESS

As stated earlier in chapter 2, the development of new systems is always based on a General Operational Requirement. The mid-range strategic objectives normally provide a time that the equipment is needed in the fleet. The length of development time can and does control the amount of Performance Capability, as previously used, that can be developed into a proposed system.

For any particular delivery schedule there is some limit to achievable capability. If more time can be allowed a higher level of capability might be developed. Again, if a capability adequate to perform the intended function on a particular mission cannot be provided within time constraints, the proposed system cannot be considered as supporting that operational requirement.

Where excess capability can be provided then Performance Capability and schedule can be traded-off in selecting the capability to develop into the system.

There is, of course, always some risk involved that the equipment will not be delivered on schedule. This is especially true when major technological breakthroughs are required, but can also occur in standard production contracts such as when major strikes occur. The penalty for failure to have the equipment operable must be assessed (in terms possibly of importance of meeting the particular objective within the time frame, or adequacy of present interim systems to achieve the military purpose). The capability to be developed into the system must be selected such that the risk of late delivery is reduced to an acceptable value.

Within the constraints provided (mission and performance envelopes) a relationship between the effectiveness (usefulness) and probable delivery schedules may sometimes be found. In some cases this will be bounded, that is, limited on one or both ends of a delivery period. If for example the system were a fire control for a new weapon, delivery before the weapon become available would serve little, if any, purpose.

Or if the equipment were for interim use until a new system with far superior capabilities was developed, delivery too close to the phase-out date is obviously uneconomical. In most cases the relationship will be highly subjective. The "decision maker" will have to assign values to the various possible combinations of capability and delivery to use in determining the desirability of the various possible courses of action (various competing systems).

2.3 UTILIZATION

As earlier mentioned, the capability of the equipment may be in excess of requirements. The excess capability is, in effect wasted -- that is serves no useful purpose. To describe the useful capability we can employ a Utilization factor, a fraction describing what portion of the available capability is used in the particular mission being considered.

Due to environmental effects the capability may at times be less than the requirements. In this case, we can consider the Utilization factor as the fraction of time that the equipment is capable of achieving the requirement within the limitations imposed by effects external to the system, even when the system is performing within specifications. The Utilization factor reflects reduction in capability, as well as use, due to influences external to the system. The product of the Performance Capability index and the Utilization factor provides a measure of usable capability within the mission requirement.

Many systems have a spectrum of possible mission requirements. The most economical set of systems is probably (but not always) the minimum number of systems that meet all the mission requirements. So each proposed system must be tested against all pertinent requirements and a system selected that optimizes the use of funds (within performance and delivery schedule constraints) with due consideration of phase-out of other systems and introduction of other systems under development.

2.4 DEPENDABILITY

The Performance Capability of a system (when working right) is useless if the equipment is not operable when it is required. Failures of the equipment during the attempt to perform the required function may prevent the accomplishment of the mission. The dependability of the equipment -- its operability when required and its reliability when operating -- can influence the effectiveness of the equipment. Two factors are involved. These are normally termed Reliability and Availability.

Availability, with certain exceptions, represents the readiness of the system to respond on demand. Reliability is the ability of the system to operate for the required period, provided it was capable of responding on demand. The dependability computation depends on the nature of the requirements.

2.4.1 Simple Reliability: Let's consider a case such as the steering engines of a ship. The requirement for the steering engines is "no failure" during a particular period. Every command for rudder angle must be obeyed -- no down time is tolerable. The use is, in effect, continuous while underway. The consequences of failure to respond with a change of rudder angle are considered unacceptable. For this example the Effectiveness of the equipment is less than the (used) Performance Capability by a factor based on the probability that it will continue operating during the required operating time. This factor is the Reliability, R. Where the Performance Capability is P, and the Utilization factor is U, the Effectiveness E is the product:

$$E = PRU$$

In this case, Availability is not meaningful since the consequences of failure are considered identical regardless of downtime.

2.4.2 Availability: Consider again a radar, this time a search radar whose sole purpose is to detect (but not track) approaching "bogies". The detection and reporting are essentially instantaneous. Once detected and reported, the approaching aircraft is assigned to a second radar set to track. As soon as the "bogie" is reported there is no further requirement on this radar in connection with this target. The operating time for this radar is continuous for a three month cruise. In this case, the Effectiveness of the radar is the Performance Capability multiplied by its Utilization and by its Continuous Availability A_C, which in turn is the probability that it is operable at any time during the three months cruise. That is:

$$E = PUA_C$$

The Reliability is considered not pertinent to the requirement, except as reliability parameters influence the Availability.

2.4.3 Combined Reliability and Availability: Assume a system such as a fire control radar. The requirement for the system is to lock on to a target -- if and when a target appears -- and direct the weapon in hitting the target. The demand can come once a day or once a month. Two things are important, -- that (a) the equipment be ready to respond to a demand if it comes and that (b) once the demand is made and the equipment starts to operate, that no failure prevents the fulfillment of the requirement.

The Effectiveness of this equipment is its Performance Capability multiplied by the probability that it is "ready" when required (the Availability, A_C), and then multiplied by the probability that it will perform successfully (the Reliability, R). In this case, the Effectiveness is the product

$$E = PA_CRU$$

It is important to note here that where the Reliability of the equipment is different in the standby mode than in the operating mode -- that is, where more failures or more frequent failures are to be expected when the equipment is operating than when it is standing by, the value of Availability should be computed based on the equipment MTBF in the standby mode.

Another illustration of this situation is a radar set whose function is to detect and track targets. In performing detection, only the radar set is used to provide signals on a scope. When a signal appears on the scope, a computer is turned on and a signal controlled by a human operator manipulating buttons and a cursor on the scope provide input to the tracking computer.

For the complete equipment the operation is bi-modal, -- detecting, Mode A and tracking, Mode B. Since the operation of the detecting portion of the equipment is necessary for the tracking operation, the effectiveness of the equipment is the capability used (PU) multiplied by the product of the Availability in mode A (A_A) and the reliability in both modes ($R_{A \cdot B}$). That is:

$$E = PUA_AR_{A+B}$$

2.4.4 Summary: As may be noted by examining the different situations, the dependability factor is determined by the way the requirements are stated. Where the primary requirement is "no failures", reliability is the primary consideration. Where the requirement is maximum "up time" Availability becomes the criterion. Where the required operation is more complex, a combination of Availability and Reliability is needed to measure the dependability.

A more general statement of Effectiveness would include factors such as Delivery Effectiveness, D, in the general relationship E = f(P,U, D,R,M) where the function f(x) merely states that the Effectiveness is some relationship between the factors to be determined from the stated requirements.

3. RELIABILITY IN SYSTEM EFFECTIVENESS

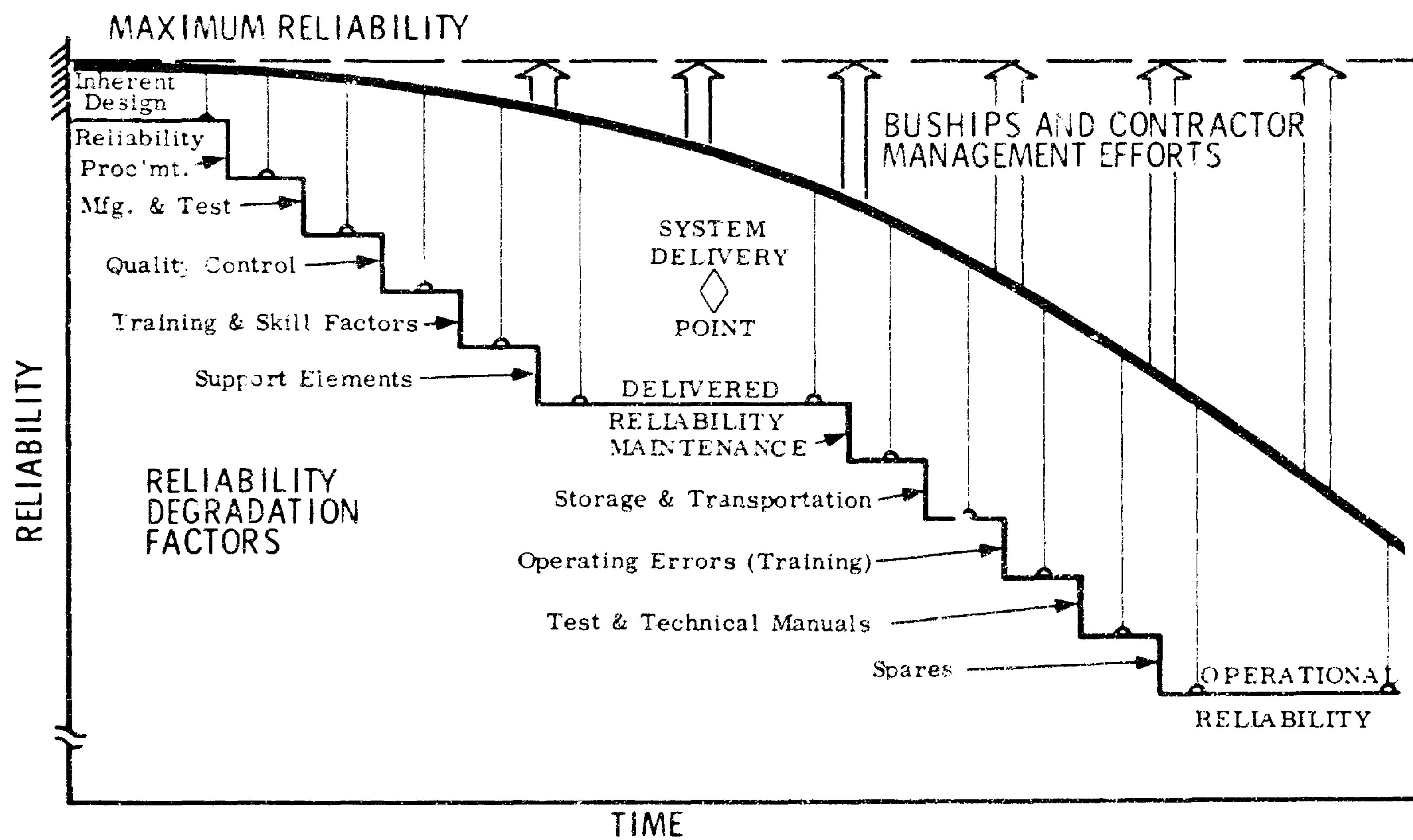
As we have seen, one of the primary parameters of system Effectiveness is the Reliability. Of these interrelated parameters, Reliability is the most susceptible to expression out of context. However, even in reliability studies, an investigation cannot be conducted unless it is extended to include related characteristics that influence system Effectiveness.

It has long been apparent that the maximum Reliability that can be achieved by any system is the amount designed into the equipment. Therefore, the requirements for design must be carefully apportioned among the various pieces of equipment and controlled throughout the design effort. Any work accomplished to make the design a hardware reality will tend to reduce the designed Reliability if these factors are not carefully controlled.

Figure 25-12 depicts most of the areas where in carefully planned control must be exercised in order to prevent undue degradation of Reliability. It also describes the action which must be taken by the Bureau of Ships in order for it to adequately control those areas for which it is responsible. It immediately becomes evident that for high operational reliability to be obtained, close teamwork is necessary between the Bureau of Ships and the contractor. Furthermore, top management must be aware of and support all pertinent elements necessary in a thoroughly coordinated manner in order to achieve high operational Reliability.

Operational reliability is one measure of system Effectiveness. For equipment which could operate continuously or upon demand without failing, this measure would be 100 percent. This figure

MGMT. EFFORT ON RELIABILITY DEGRADATION FACTORS



can at best only be approached asymptotically as the art of system design advances.

3.1 ESTABLISHING REQUIREMENTS

One approach to establishing a requirement is to determine the unreliability which we are willing to tolerate in a system. Obviously if its function is critical to mission success, then we will tolerate relatively few failures. From this approach, we can derive a principle which is one basis for establishing a reliability requirement -- namely, that the relative importance of the system to the ship's mission is influential in determining the assigned requirement. The requirement may be expressed simply in terms of the failures permitted during a given mission type and duration under specified conditions.

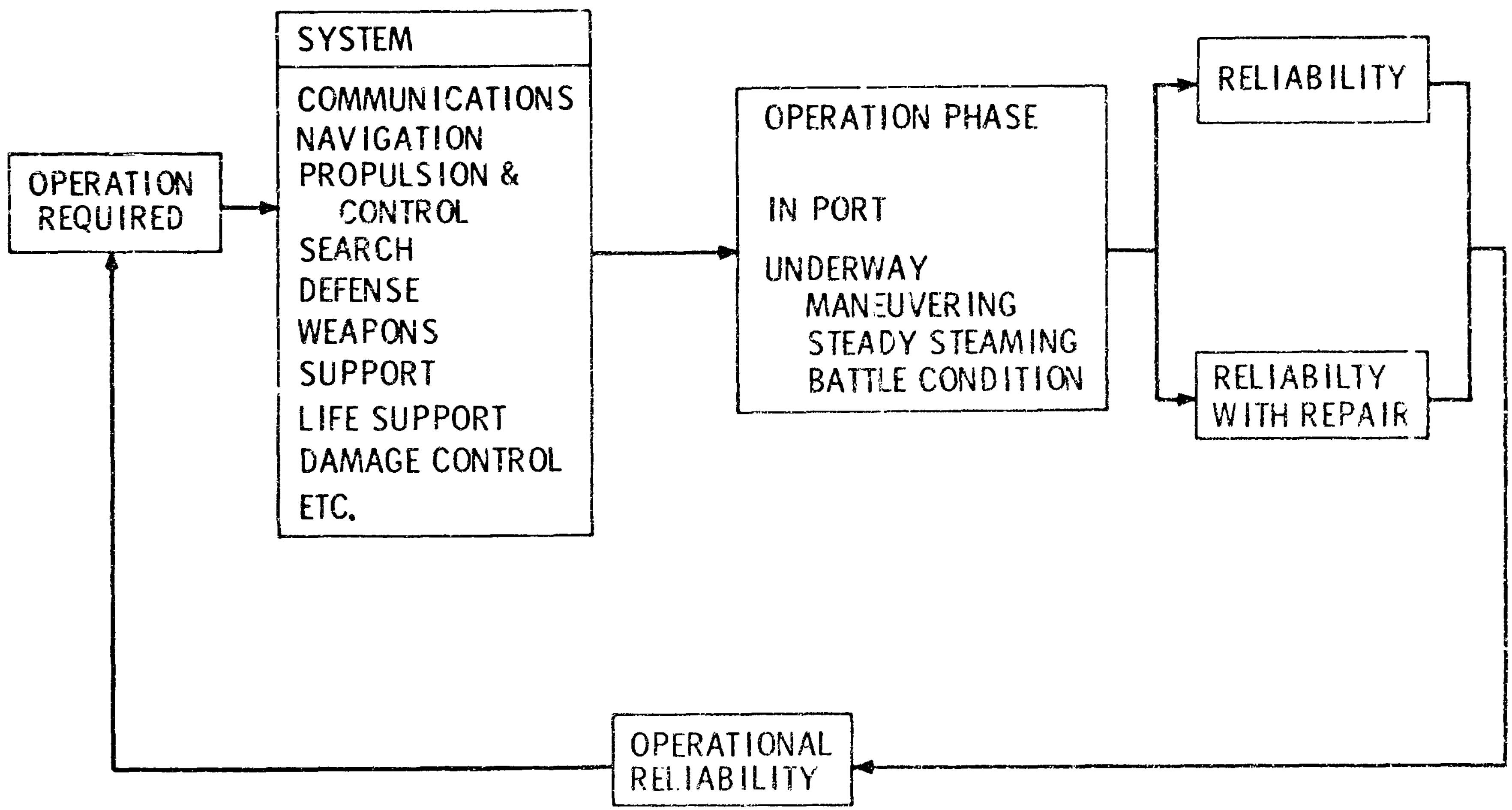
Following this reasoning a step further, why not merely state that no failures will be permitted, so that we have 100 percent reliability of the system during the mission? This reliability is probably unattainable and impractical even as a design goal. In design of a ship, system or part, reliability is in competition with Performance Capability, cost, time, logistics, and obsolescence. The latter would probably be attained prior to 100% Reliability even if all other parameters were most favorable to reliability.

This is not to say that extremely high reliability cannot be achieved. It can, but often it cannot be realized economically, or without undue penalty upon performance or schedule. We know from experience that reliability of a system can often be increased significantly within the state-of-the-art using the approaches given in chapter 13. The improvement to reliability is usually limited by cost, schedule, etc.

3.2 METHOD OF ANALYSIS

In the application of reliability principles, to determine operational reliability requirements, it is necessary to identify the events which comprise a system activity cycle. For ships, the activity cycle consists of various types of operational phases. The logical sequence of events considered for the analysis of operational reliability is shown in Figure 25-14. The operational period for each system is from system turn-on throughout the operational period to system turn-off. For some systems (propulsion) this may include the complete Underway period. For other systems (communications) this includes both At Anchor and Underway. For still others (weapons) this may include only

LOGIC OF RELIABILITY ANALYSIS



Battle Condition with readiness requirements for patrol or war zone cruising.

Reliability parameters contained in each operational phase are mission required, system required, and use factors. For a particular type of operation, this would include the elements requireing reliability measures in preparing for sea, transition to an operating area, on station or patrol, engagement action, transition to port. Startup and checkout of each system are considered part of the operation and the reliability measure includes this operation time.

The extent of unscheduled maintenance performed both at anchor and underway is dependent upon the requirements for the present and future operational phases. Scheduled maintenance, both at anchor and underway, includes major maintenance functions of periodic inspections, minor inspections, and modification of equipment.

3.2.1 Operational Reliability Analysis: In the operational phase of the reliability analysis, all of the events are considered from deployment order to systems shutdown after the operational phase is over. Many variables are involved within each operational phase, such as different missions required, variations of operational parameters within each mission type, different preparation-for-sea reliability values, and variability of mission success criteria. However a complete general analysis to determine operational phase reliability for any combination of the variables is possible. The method of attack is to select the design mission for an extensive analysis and then to carry the analysis over to other missions to the extent possible.

To reduce the amount of computation necessary, only a finite number of significant points within the mission profile is usually selected to measure actual reliability values. These points may be the equipment required for in port use, the equipment necessary for the on station or patrol phase, equipment necessary for engagement action, and transition back to port. Due consideration must be given to on-board maintenance capability and the operability time of all equipment.

One of the most important uses of the system effectiveness concept is to make it possible for the maintenance support planner to obtain a reliability measure for a mixed family of missions from inherent failure-rate principles. These measure of reliability indicate the failure-induced frequency for maintenance. However, the maintenance support planner knows from experience that failures occur which are not induced solely by equipment design characteristics. The ratio between the total failures requiring maintenance action to failures induced by equipment design only is actually greater than 2 to 1. However, systematic approaches are available which can be applied to derive the conversion ratio of MTBF to MTBM.

MTBF/MTBM Relation: To clarify the problem of converting MTBF to MTBM, it is necessary to consider the basic principles of reliability. The characteristic failure rate curve of equipment is shown in Figure 25-17. The random period of equipment operation contains not only the design failure rate but others such as misuse of equipment by the operator, maintenance induced, and operation in an environment outside the original specification. These misuses of equipment can also increase the normal random failure rate.

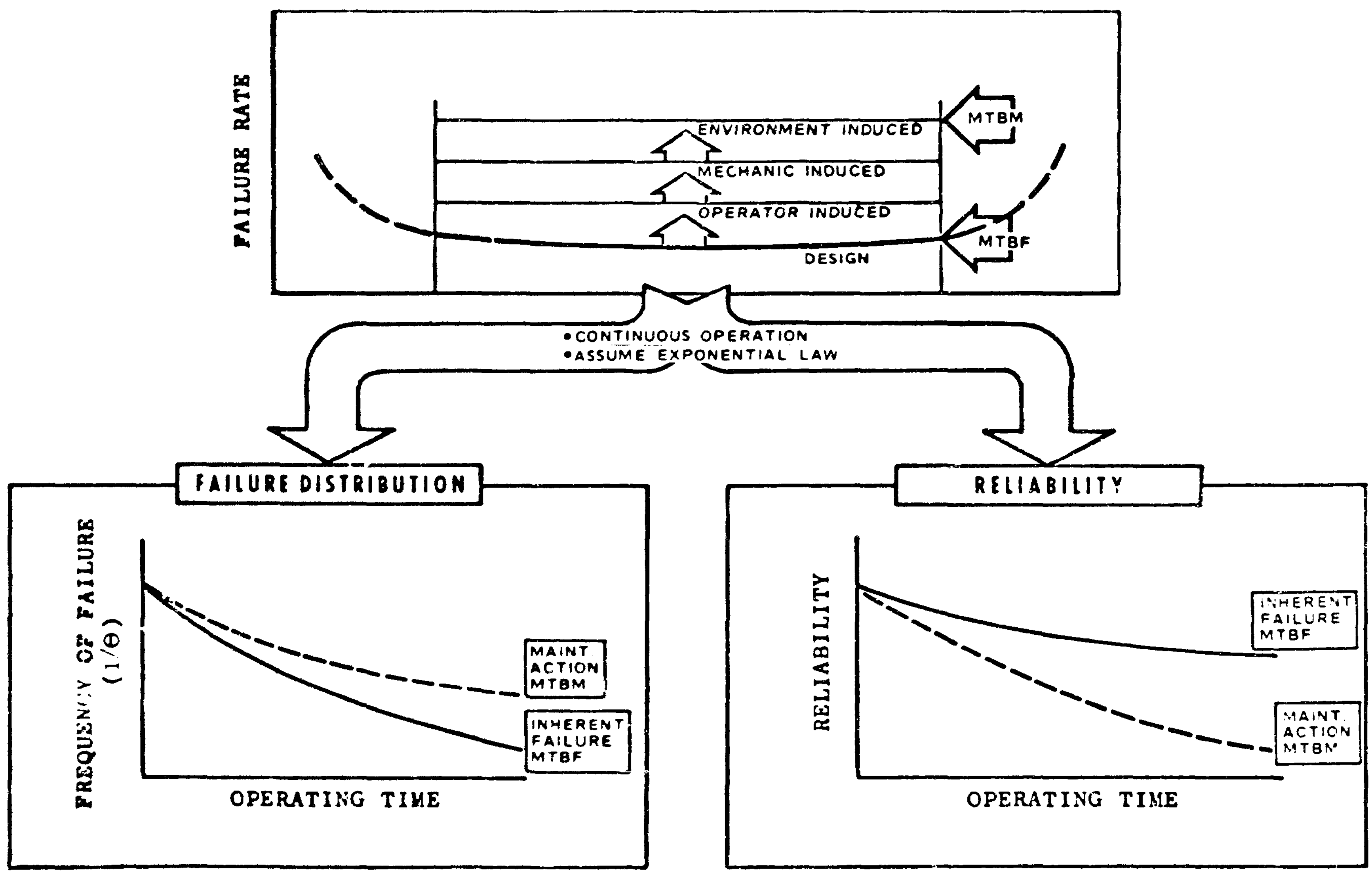
The separation of MTBF and MTBM on the life characteristic curve generates changes in both failure distributions and reliability measures as shown in Figure 25-17. It is readily seen that the failure rate of MTBM equals K times the MTBF failure rate where K equals MTBM divided by MTBF.

In the failure distribution graph, MTBM is seen to have a higher frequency of failures with respect to time than MTBF. It is recalled that frequency is equal to the reciprocal of MTBF. In like manner, the frequency of MTBM is a reciprocal. Since MTBF is greater than MTBM, it follows that for any one point of operating time the MTBM induced frequency is greater than the frequency generated by MTBF.

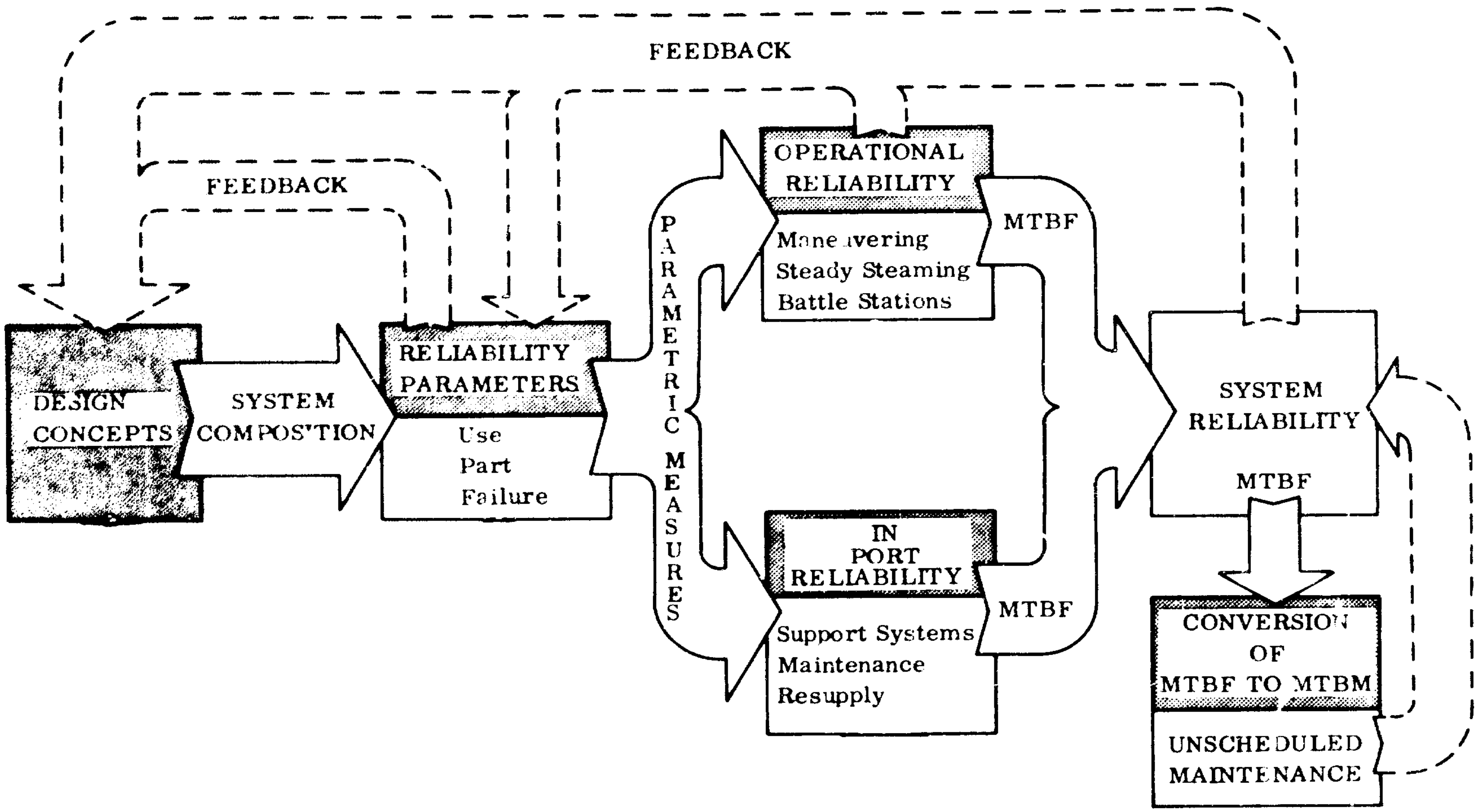
The MTBF and MTBM are shown in Figure 25-17. As expected, the probability of equipment being operable without a maintenance action is less than the probability of operating without a failure.

3.2.2 Study Approach: Reliability studies for systems use a dynamic approach by expanding the reliability concept to determine measures which can be used to evaluate the effects of operational activities, such as in-port use, operational readiness, and maintenance, or equipment operability. In Figure 25-18 the study approach to system reliability is summarized. Corresponding design feedback loops are included. As noted, the study of reliability begins with the design concept. Through reliability measurement functions, an MTBF is obtained for each equipment for the different modes of operation. This MTBF measure is used to develop a composite MTBF measure for operational reliability.

MTBF / MTBM RELATION



STUDY APPROACH



The step between Mean-Time-Between-Maintenance action (MTBM) is the relationship between reliability and maintenance. Reliability dictates the non-scheduled maintenance job and indirectly the scheduled maintenance job. Maintenance, in turn, determines the degree of reliability restoration, based upon the efficiency with which the maintenance job is accomplished.

4. RELIABILITY AND MAINTAINABILITY IN SYSTEM EFFECTIVENESS

The achievement of the desired objective, capability of successful operation of equipment, demands a dynamic reliability program which serves to control the development and design of the system from the conceptional phase throughout its production and operation. Both the Bureau of Ships and contractors are making progress in increasing the validity and application of reliability integration processes. The importance of reliability in the system program is depicted in Figure 25-20. As shown the reliability measure of Mean Time Between Failure (MTBF) is determined by design computation. This measure denotes the operability and, conversely, the inoperability of equipment. Inoperability means that equipment has failed and the failure has resulted in system downtime and the need for logistic support.

Because of its effect on equipment operability, system downtime, and logistics, reliability is a leading contributor to an effectiveness measure. In operational terms, it can be said that the measure of operational readiness, redeployment rates, success of operator, maintenance specialists, test equipment, spares, etc., are directly dependent upon the measure of equipment reliability and indirectly affect the scheduled maintenance.

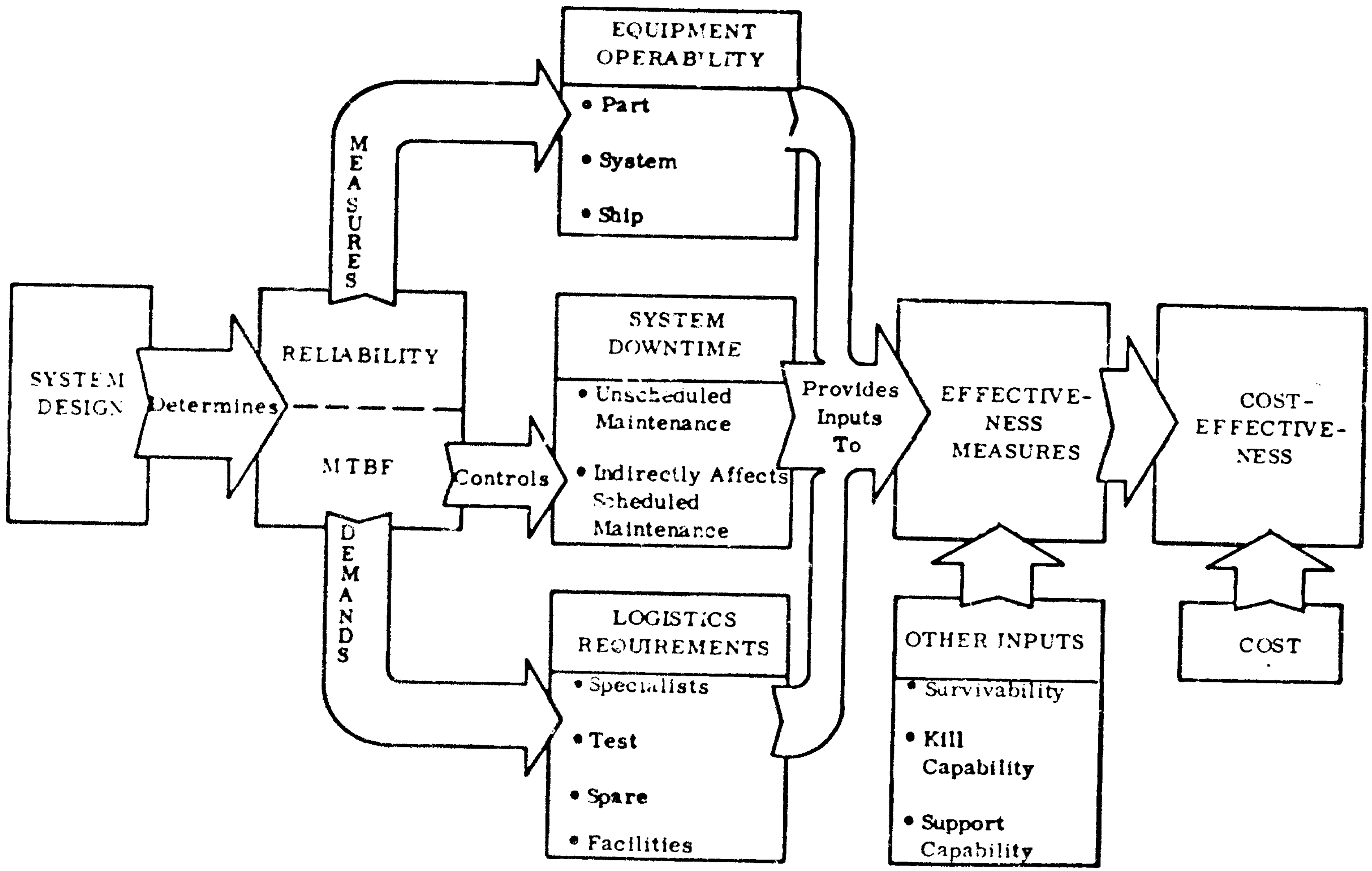
We will consider only briefly the trade-off relationships between the Effectiveness measures, Reliability and Maintainability, as a function of system Availability. Availability is considered to be the operational time divided by the total time, i.e.,

$$\text{Availability} = \frac{\text{total operational time}}{\text{total time}}$$

For example, if we had a system committed to an operation for 30 days, the total time would be 30 x 24 or 720 hours. If during this period, the system were down for corrective maintenance for a total of 48 hours, the Availability of the system would then be:

$$A = \frac{720 - 48}{720} = .92.$$

RELIABILITY CONTRIBUTION TO EFFECTIVENESS



It should be apparent that the restoration time of 48 hours can be caused by many factors.

Availability may be portrayed conceptually as follows:

AVAILABILITY

RELIABILITY	MAINTAINABILITY
Time to failure	Time to restore

Availability can be described as

$$A = \frac{MTBF}{MTBF + MTTR}$$

where MTTR = Mean Time to Restore, and consequently, for any given Availability, is directly porportional to the Mean Time Between Failure. For a given Availability, this implies that by doubling the MTBF, we can accept twice the maintenance time.

A specified or required Availability can be obtained from many different combinations of Reliability and Maintainability. Consequently, the allocation of fixed resources should depend upon (a) the ease and relative cost of increasing these elements and (b) the increase in Availability accompanying specified increases in each element or combination therein.

Within the limitations previously discussed, Reliability and Maintainability can be used to substitute for each other over a wide range of Availability in a complex system. Efforts within the limitations of economic and technical constraints may be allocated to develop more or less Reliability, and relatively more or less Maintainability in attaining either increases in Availability or minimum cost levels of Availability. Therefore, the substitution of Reliability for Maintainability becomes an appropriate concept for decision-making purposes.

5. SYSTEM EFFECTIVENESS MODELS

Reliability models are used to explore and validate alternate preliminary design approaches. Models may be used to study complexity, predict Reliability achievable in design, predict ultimate Availability based upon Reliability and Maintainability, and to determine the growth of Reliability during the design. In a sense such models are limited to relating Reliability and Maintainability as system design parameters. In this chapter we see a broader use of the system Effectiveness models to establish a ship's mission Effectiveness requirement in terms of operational and deployment factors, such as readiness rates, mission mode Reliability and Maintainability. The latter uses are currently being expanded to include all other elements related to Effectiveness, including cost and schedule.

It now appears that such a full effectiveness concept is feasible, and evolutionary. Techniques are being developed for quantifying the remaining elements so that computer technology may be employed to develop a single measure that is based upon optimization of the fundamental measures of total operational Effectiveness. The rapid development of this total operational Effectiveness concept is a worthy goal of managers interested in naval efficiency (refer to Figure 25-23).

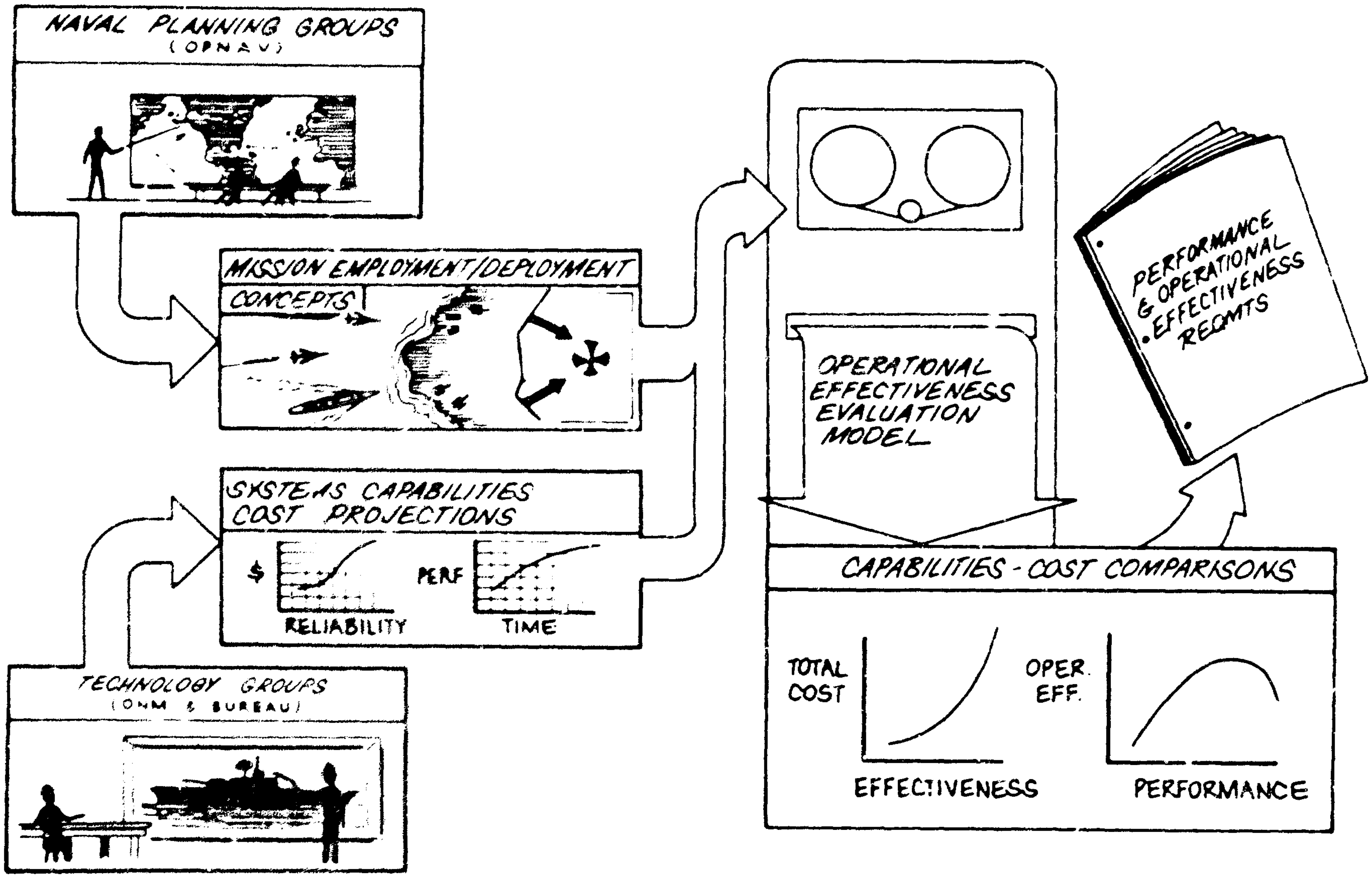
The procurement of costly complex systems is a risky business. Despite all efforts to thoroughly assess proposals prior to award, the contractor selection process is still far from ideal. Vagueness, particularly with regard to the ultimate Effectiveness, is characteristic of most. If the award is based upon lowest Acquisition Cost, it could well prove to be the most costly system, unless the parameters other than cost, schedule, and performance are clearly treated with the importance they deserve. See chapter 23, section 5.1.2, and chapter 26.

The use of models as a means of validating "proposal promises" could improve the contractor selection process. This method could be used by requiring the submittal of a model as part of the proposal. If such a model clearly substantiates a proposed approach as a valid one, the accepted model values can be invoked in specifications. The model can be used to determine the buyer and seller risks associated with demonstrating Reliability and Maintainability values when demonstration and correction of defects are required under Fixed Price contracts. The model can be an invaluable tool in controlling the achievement of reliability during a long design and development program where numerous changes are introduced. The effect of such changes on Reliability can be determined at any "break-in" point. It serves also as a built-in Reliability and Maintainability audit apparatus that the Contracting Officer can examine at any time.

Through comparison of input allowances for degradation with the actual degradation, the model can also be used to determine the control of reliability subsequent to design. As a final step, it obviously can assess the achievement of reliability and maintainability by comparing the requirements with the operational

HOW ARE THESE TECHNIQUES EMPLOYED?

GENERATION OF SYSTEM REQUIREMENTS



experience.

While the models and computers are extremely useful tools, they do not replace Navy management. Neither do they substitute for good reliability design practices, or quality control. Despite the wonders of the computer, and of Reliability Engineering as the science of excellence, we are still dependent upon Admirals, civil servants, seamen, and contractors to provide a ships worth of confidence in every ship.

6. REFERENCES

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2. Handbook, Reliability Engineering, NavWeps 00.65-502, 1 June 1964.

3. System Reliability Engineering, Gerald H. Sandler, Prentice-Hall Technology Series, 1963.

Chapter 26

COST-EFFECTIVENESS

Chapter 26

COST-EFFECTIVENESS

This chapter is concerned with a very old problem. Just how old, and how universal, is apparent in this quotation from Shakespeare in King Henry IV, part 2, Act I, scene 3:

> .....When we mean to build,
> We first survey the plot, then draw the model;
> and when we see the figure of the house,
> then must we rate the cost of the erection;
> which if we find outweighs ability,
> what do we then but draw anew the model
> in fewer offices, or at last desist
> to build at all?

For the last several years we've had a shiny new name for the same old solution to the same old problem. We've called it "cost-effectiveness." But let's have a look at the modern problem.

1. OPERATIONAL COST EXPERIENCE

During World War II, with its unprecedented dependence upon electronic gear, the consequences of unreliability became painfully apparent. After the war many military surveys were made to evaluate the problem, and the new reliability technology was developed under forced draft.

But the problem did not go away. It became obvious to our military leaders that the great cost of unreliability was, and still is, using a very large share of our defense dollar resources. Funds needed for more or better weapon systems are being pre-empted by high maintenance cost, and sometimes by ill-considered development and premature production. Here are some quotations of our military leadership:

1.1 DOD EXPERIENCE

Robert S. McNamara, Secretary of Defense, 28 March 1963 speech to the Senate Joint Economic Council

"All too often large-scale...developments, and even production programs, have been undertaken...before we had clearly determined that there existed a suitable technological base,.... what it would cost,....and whether the capability would be worth the cost. As a result,...changes are being made." One change is DOD directive 3200.9, excerpted in Figure 26-3.

EXCERPTS FROM DOD DIRECTIVE 3200.9

Signed by Robert S. McNamara

Prerequisites to PDP:

The mission and performance envelopes are defined and are optimized for technical feasibility and COST EFFECTIVENESS;

The COST-EFFECTIVENESS of the proposed item has been determined to be favorable in relationship to the COST-EFFECTIVENESS of competing items on a DOD-wide basis.

Participating Organizations:

At no point during the competition shall cost be the sole criterion for decision or selection.

Requests for Proposal:

It is essential that the RFP encourage alternatives and stimulate initiative and creativity by the contractors.

Total System Tradeoffs:

Tradeoffs shall be used to obtain.....an optimum balance between total COST, schedule, and operational EFFECTIVENESS for the system. Total cost means the total cost of acquisition and ownership. Operational effectiveness includes ....."pure" performance, reliability and maintainability; system includes the hardware,........facilities, personnel,.......etc.

Effective Date:

Immediately (February 26, 1964)

Charles J. Hitch, Comptroller, Dept. of Defense (2, p.63)

"Military requirements are meaningful only in terms of benefits to be gained in relation to their cost. Thus, resource costs and military worth have to be scrutinized together. The new planning-programming-budgeting procedure facilitates the performance of cost-effectiveness studies since it brings together both programs and costs in context with major military missions of the Defense Department projected over a period of years."

"For example the RDT&E subactivity "Polaris Submarines," for which $380 million was included in the 1963 budget, becomes part of the program element "Polaris System" for which over $2 billion was included. (This in turn) is part of the grouping "Missile Forces, Sea Based," which in turn is part of the major program "Strategic Retaliatory Forces."

"The key point for fiscal control, for both budgeting and programming purposes, is the RDT&E subactivity. In the case of the program elements, our reporting and controls are being designed primarily to relate physical performance -- i.e., progress in achieving the objectives of each program, -- to total cost to complete the development and investment phases.. ...and the annual cost of operating it. The really important financial question in making decisions about the Polaris system, for example, ...is not how much the program will cost during any one budget year, but how much it will cost to complete."

James R. Bridges, Director of Electronics, ODDR&E (3)

"We may not (be giving the engineers) enough time or money for thorough design, engineering and test. In proposals, a prospective contractor....must include realistic estimates of the time and cost (to satisfy reliability requirements). We (must) balance the cost of failure against the true value of early success."

1.2 NAVY EXPERIENCE

Hon. Victor M. Longstreet, Assistant Secretary of the Navy for Financial Management (42)

"Much has been written about the use by the Defense Department of certain techniques as a basis for making better decisions. These techniques have various names such as Cost-Effectiveness, Systems Effectiveness,....the purpose of which is to take a hard look at everything, to explore a variety of possibilities, to come up with facts, to apply military experience, to test, to evaluate, to weigh judgments.....One very important ingredient, - to put all of this down on paper for all to see, to study, and to question."

Rear Admiral Emerson Fawkes, USN, Assistant Chief, BuWeps, R&D, Test & Evaluation (4)

"The cost of acquisition is like an iceberg; it fails to reveal the ownership cost of 4 to 10 times the acquisition cost."

"One of the most serious of our problems is the limited experienced manpower capability to which the Navy has access. This in turn is reflected in training capabilities required to operate and maintain these complex systems. 70% of maintenance is done by "first cruise" sailors. An SRI study indicates that direct cost per first class electronic technician is $32,953 per year."

"The use of cost/effectiveness ratio in making technical, management, and military decisions is the way of life. Major decisions...must be made in the light of the technical, economic, and military "figures of merit."

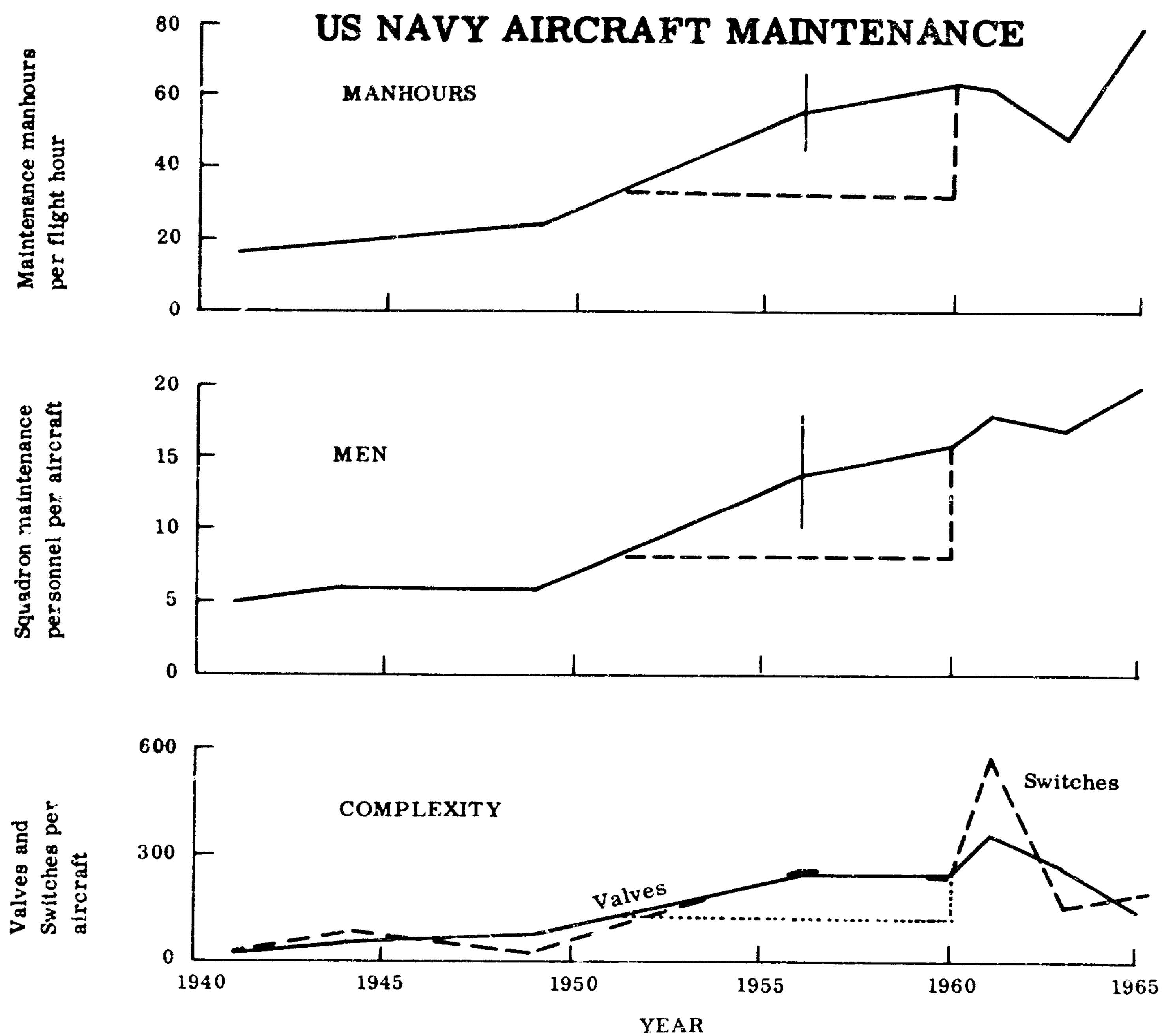
"We must obtain a major advance in weapon reliability and maintainability. It is here that the greatest cost is experienced, and here that the greatest improvement in system effectiveness can be obtained. A five or ten percent improvement is not enough."

"The value engineers passion for simplicity and the reliability engineers analytical training should combine to attack our spiralling complexity problem."

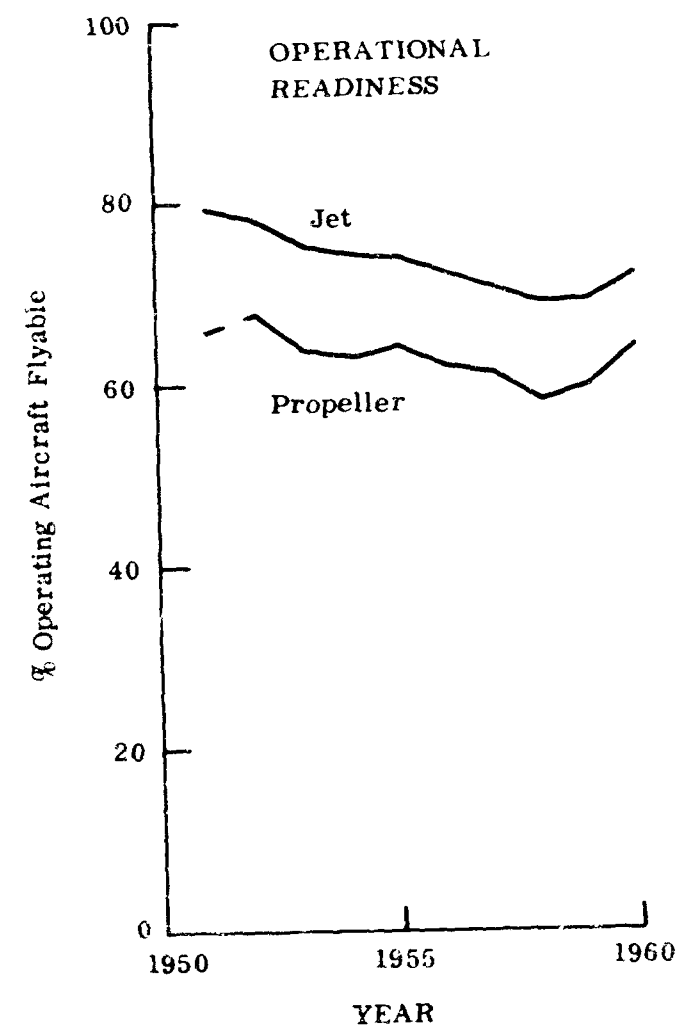
Future Trends in Carrier Aviation, US Navy survey (5): Figure 26-6 shows the trend of complexity, and consequent unreliability, upon both manpower level and manhour cost, from 1941 to 1965. Note particularly the period 1951 to 1960, when both manpower level and manhours (most of maintenance cost) doubled, permitting the inference that maintenance time was not improved.

Figure 26-7 essentially confirms this. It shows that Operational Readiness, or Availability, has dropped 3 to 10% in the same period.

BIMRAB (Bureau (Weps) Industry Materiel Reliability Advisory Board) Survey on Industry Reliability Programs (6): This 20-


US NAVY AIRCRAFT MAINTENANCE
MANHOURS
Maintenance manhours per flight hour
80
60
40
20
0
MEN
Squadron maintenance personnel per aircraft
20
15
10
5
0
COMPLEXITY
Valves and Switches per aircraft
600
300
0
Valves
Switches
1940
1945
1950
1955
1960
1965
YEAR

US NAVY AIRCRAFT



question survey by BuWeps in the Spring of 1960 was sent to 196 of its contractors. Among the results is Figure 26-9. Participants were asked what they considered to be the deterrents limiting reliability to present state of the art, and to rank their selections from 1 to 5 in order of importance.

Clearly the contractor consensus is that funding is not consistent with the manpower necessary to get the desired reliability. Incidentally a separate Air Force survey in 1961 to 72 contractors on the same question resulted in a 30.4% funding figure, a confirmation of the Navy 30.8%.

1.3 AIR FORCE EXPERIENCE

Lt. General Howell M. Estes, March 1964 (7)

> "Maintenance costs on today's systems have risen to...almost 30% of the Air Force budget. Maintenance of military electronic equipment ranges between 60 and 1000 times the initial costs. Complexity and maintenance creates an almost insatiable demand for large quantities of highly trained manpower. The progress we have made to date in system reliability...has simply not been adequate in an overall sense."
>
> "Failure of a $2 item not long ago caused the loss of a $2.2 million launch vehicle. In another program, failure of a $5 thermal shield resulted in a $23 million disaster. Failure of a $25 fuel valve caused loss of a vehicle and damage to the site totalling $22 million. These dollars would have bought a lot of additional reliability in these programs."

Air Development Center, Research Contract (8): The annual support cost for a representative ground communications equipment was about 12 times the original cost. For navigation it was 6 times and for radar 0.6 times.

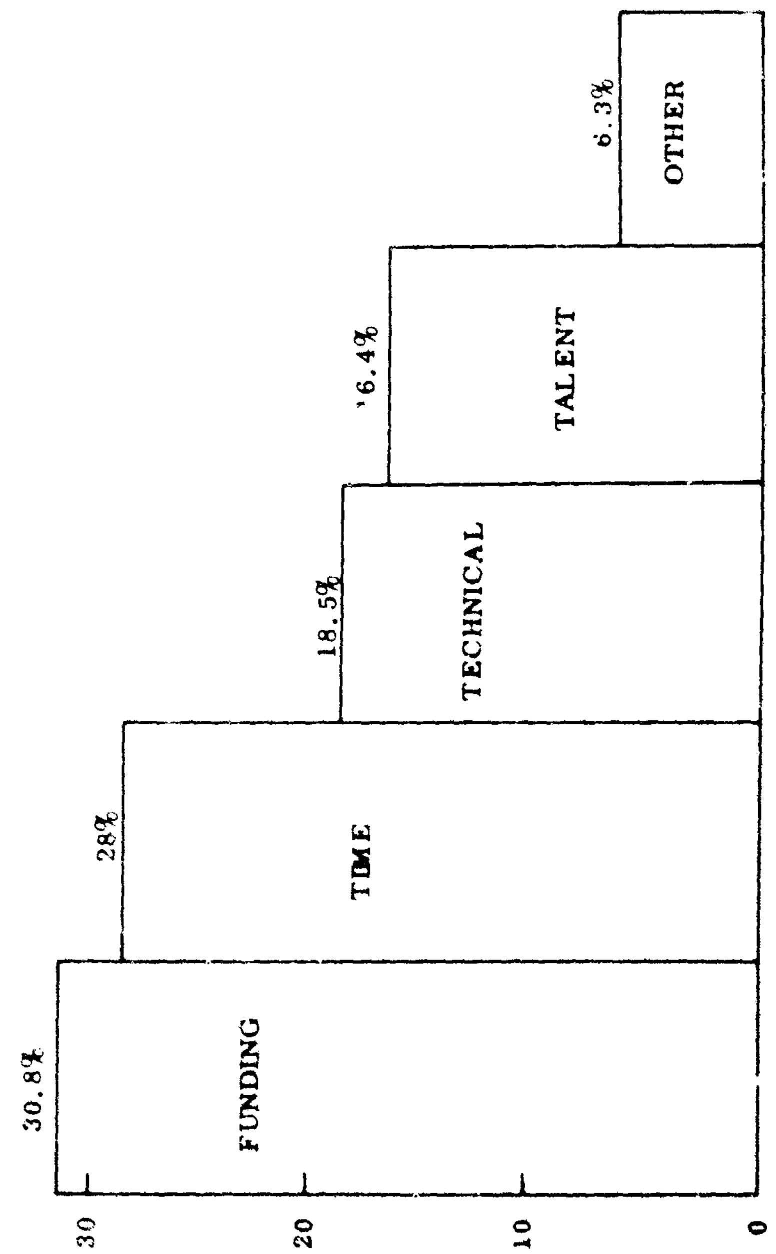
2. THE COST-EFFECTIVENESS BALANCE

We have heard rather overwhelming evidence of the cost of maintenance. Maintenance is primarily a consequence of unreliability. We have heard the DOD and Navy decision to put quantitative reliability and maintainability (R&M) into applicable future contracts. But it's more easily said than done.

The fact is that reliability achievement costs money. Improved engineering and quality control practices often improve MTBF by a factor of 2 to 4. But for many situations we need 10 or 100

DETERRENTS TO RELIABILITY

US Navy BIMRAB Survey



times improvement, sometimes 1000. Far from being impossible, there are design approaches that will get such order of magnitude improvement, as outlined in chapter 13. But they cost money for design time, perhaps for added manufacturing cost, and perhaps for extensive test programs.

So we are in the position of having to spend more money in order to save money in maintenance. The question is "how much reliability and maintainability is justified?" How much is worth the expenditure?

2.1 THE OBJECTIVE

In order to answer this question we have to establish a clear objective. Is the objective "maximum reliability?" Certainly not, because the cost of achieving it could far offset the maintenance savings. Is it "minimum total cost?" Not necessarily, because often a moderate cost beyond "minimum" brings substantial reliability improvement, and in turn increased system effectiveness, well worth the extra cost.

What we are really after is maximum system accomplishment or worth, in relation to total cost to acquire and maintain the system for its lifetime. In recent years this has come to be called the "cost-effectiveness" of the system, and there are three common approaches to its optimization. These are design for:

(a) The maximum ratio of effectiveness to total cost

(b) The maximum effectiveness for a given total cost, and

(c) The minimum total cost for a given required effectiveness.

These approaches do not always lead to the same result, which consideration is beyond our scope here. But in a very general way we can say that we always want to get (a) the most effectiveness per dollar, but we may have to back off from that optimum to (b) live within available funds, and/or (c) at least achieve some minimum value of effectiveness.

2.2 EFFECTIVENESS

What, actually, do we mean by Effectiveness? The term is still evolutionary, and many conflicting definitions have been used. As developed in chapter 25, the one we find most broadly useful and realistic is this:

Effectiveness is a quantitative index expressing actual accomplishment or worth of an operational system or component. It is a function of

(a) Performance Capability,
(b) Delivery Effectiveness,
(c) Reliability and/or Availability, and
(d) Utilization

It may be the simple product of these factors.

Performance Capability is a quantitative figure of merit expressing the system or component capability of performing desired functions, assuming no delivery delay, no failure, and full utilization.

Delivery Effectiveness is the ratio of system or component effectiveness as degraded by late delivery, to the effectiveness had it been available when needed.

Reliability is the probability that the system or component will perform its intended function for a specified period under stated conditions.

Availability is the fraction of the total desired operating time that the system or component is operable.

Utilization is the fraction of performance capability actually utilized due to the specific application and environment encountered. It includes all effectiveness degradation due to causes external to the system or component itself.

Thus in a very simplified way we can see that by starting with a quantitative index of Performance Capability, and multiplying it by realistic "derating" factors (due to delivery delay, unreliability, downtime, and incomplete utilization), we get an Effectiveness figure that expresses realistic accomplishment or worth. Many systems require something more complex than this simple product, but it serves to visualize the problem.

2.3 TOTAL COST

Now what do we mean by "Total Cost" of a system? We mean all costs for the useful lifetime of the system. To use the DOD terminology, Total Cost is the sum of "Acquisition Cost" for development and production, and "Ownership Cost" of operation, maintenance, and consequence of failures.

Development Cost is the total cost of operations analysis (during conceptual phase), system design (during conceptual and definition phase), hardware design, hardware prototypes, test, evaluation, and schedule slippage for this phase.

Production Cost is the total cost for quantity procurement, manufacture, installation, tests, training, and schedule slippage for this phase.

Operation Cost is the total cost, for the system or component lifetime, of those personnel, facilities, utilities, consumables, and special inputs required for operation, excluding those for maintenance.

Maintenance Cost is the total cost, for the system or component lifetime, of those personnel, facilities, spare components, logistics, and diagnostic aids required for maintenance.

Consequence Cost is the total cost, for the system or component lifetime, generated external to the system or component as a consequence of its failures. These may include damage or loss of other systems or components including human productivity.

Now it will be apparent that these costs are all determined by the above Effectiveness factors. For example Development Cost is a primary function of the required Performance Capability, but also of the required delivery, and the required Reliability and/or Availability. Maintenance Cost is a primary function of the achieved Reliability and/or Availability, but also of Utilization, and to a lesser extent the others.

2.4 SAMBA

The Bureau of Ships has established a broad program called Systems Approach to Managing BuShips Acquisitions (SAMBA). Its objective "is to make significant and continuing improvements in the management of all aspects of the system acquisition process. Its Annex C, Engineering Considerations, contains sections 4.2.1 on Cost of Acquisition, 4.2.2 on Cost of Ownership, 4.3 on Reliability/Cost Relationships, and 5.2 on Reliability. In general it recognizes the identical relationships discussed in this chapter 26, and recommends a system approach such as we have detailed herein.

2.5 EMEC

The Department of the Navy has established the Electronics Maintenance Engineering Center (EMEC) to (a) review new equipment, (b) monitor fleet experience, (c) analyse failure data, (d) review parts support, (e) evaluate training effectiveness and manpower deficiencies, and (f) prosecute corrective action. The Center should find considerable utility in the techniques to be discussed in this chapter, as well as several others.

3. TRADEOFF ANALYSIS

Having nailed down, in very abbreviated fashion, what we mean by Total Cost and by Effectiveness, let us turn to the relationships of their constituents, and constituent impact on Cost-Effectiveness.

Figure 26-14 provides a broader picture of the overall tradeoff and cost relationships. At the left we note Acquisition Cost "top of an iceberg," which provides the funds to achieve required Performance Capability, Delivery Effectiveness, Reliability and Maintainability, and the inevitable added cost of delivery slippage, if any.

Ownership Cost, then, is the sum of the operational costs related to Performance Capability, the maintenance and logistic costs generated by unReliability and minimized by Maintainability, and the Consequence Costs generated by failures, delivery slippage, etc. Total Cost is then the sum of Acquisition and Ownership Costs, the whole iceberg.

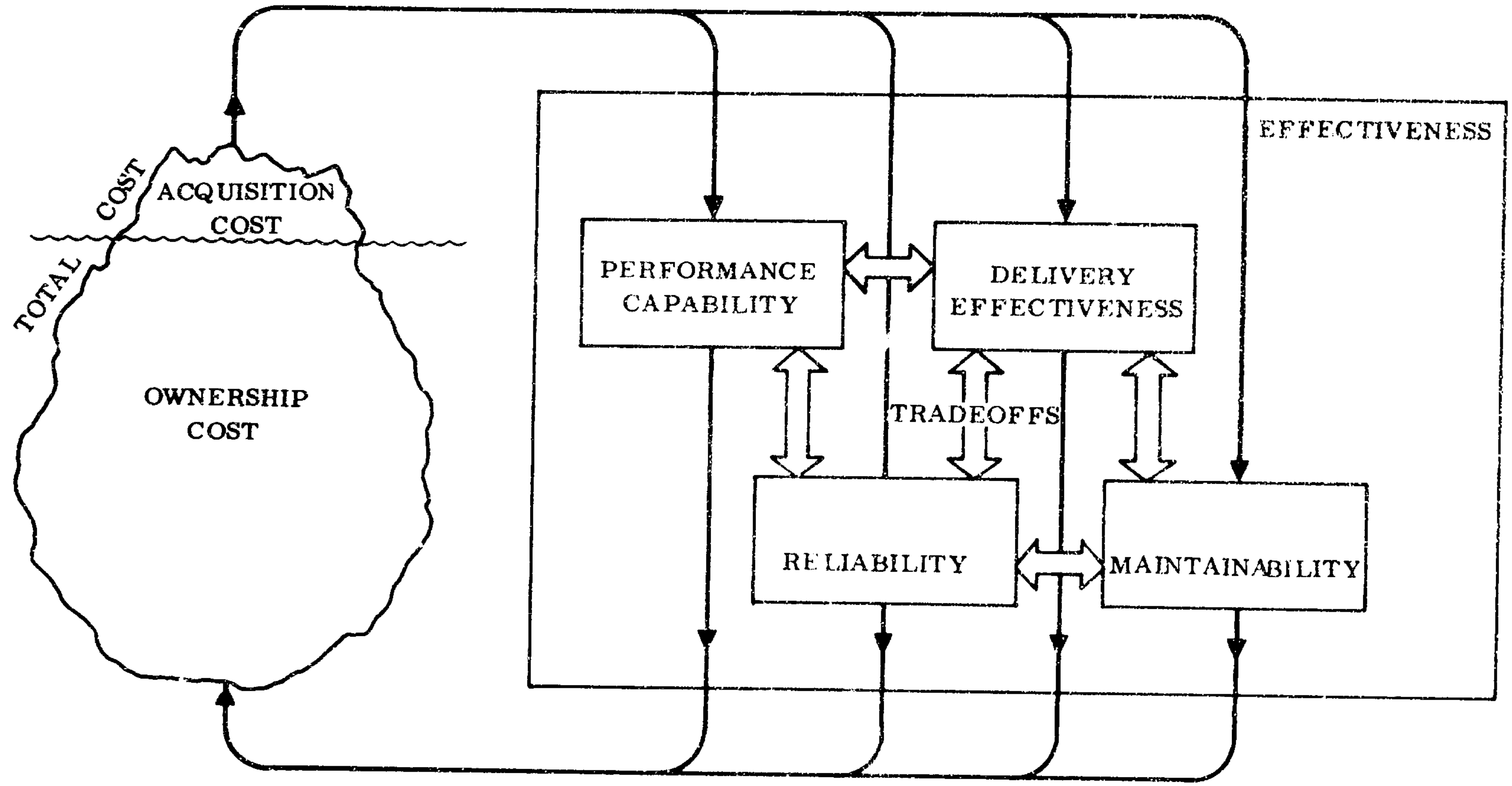
The design objective is always to get the most Effectiveness for the least Total Cost, which is rarely possible, because they rarely coincide. But it is not only possible but imperative to design for (a) the maximum ratio of Effectiveness to Total Cost, as constrained by (b) the maximum Effectiveness for a given Total Cost, and/or (c) the minimum Total Cost for a given Effectiveness.

It is not necessary to have a comprehensive "system model" or "reliability model" to predict Cost-Effectiveness, except to the extent that such models may (or may not) be needed to predict Performance Capability, Reliability, Maintainability, and Delivery Effectiveness (from Pert). It does not have to be complex.

During design, at any level of the system, the design engineer is constantly making decisions between alternatives. Many of these decisions involve "tradeoff", or sacrificing a little of one attribute to get enough of another. In particular, the design engineer must learn to trade off Performance Capability,

TRADEOFFS FOR COST-EFFECTIVENESS

HOW MUCH RELIABILITY IS REQUIRED AND JUSTIFIED?



Reliability, Maintainability, and Delivery Effectiveness with each other, as shown by the heavy arrows in Figure 26-14, to the extent that Effectiveness is thereby improved and/or Total Cost is reduced.

3.1 COST-EFFECTIVENESS RATIO

In section 2.1 above we established a primary objective of the maximum ratio of Effectiveness to Total Cost, recognizing that there may also be constraints of maximum cost and/or minimum effectiveness. In order to simplify the picture we will use the ratio henceforth:

$$\text{Cost-Effectiveness C-E} = \frac{\text{Effectiveness } E}{\text{Total Cost } C_t}$$

For Effectiveness we can use the product (9,10) of Performance Capability P, Delivery Effectiveness D, Reliability R, and Utilization U. For total cost we can use the sum of Acquisition Cost C_a and Ownership Cost C_u. So:

$$\text{Cost-Effectiveness C-E} = \frac{PDRU}{C_a + C_u}$$

Keeping in mind that for many systems Availability A (which accounts for Maintainability) is logical in place of Reliability R, and for many the product AR is logical, we can use this expression to visualize the tradeoffs involved. For example if, for the desired Performance Capability P, the Delivery Effectiveness D would be poor (take too long), the Bureau would consider reduced P to get better D without unduly increasing Acquisition Cost C_a.

Similarly if desired Reliability R would require total expenditure ($C_a + C_u$) exceeding allocated funds, the Bureau might consider later delivery (lower D) to get more design and test time for R, or fewer functional frills (lower P) to increase the Reliability R.

In this course, we are concerned only with Reliability and Maintainability, and implicitly Availability. The above cost-effectiveness equation is a very powerful tool for balancing tradeoffs of R and M with each other and with P, D, U, C_a and C_u. Such balancing of all for maximum Cost-Effectiveness must be done. In fact it has been done intuitively, if not analytically, for most systems. But intuition is far from trustworthy for very complex systems.

To illustrate the analytical use of this tool, we will "suboptimize." That is, we will examine the tradeoffs between Reliability, Acquisition Cost, and Ownership Cost, assuming that the other tradeoffs will not substantially alter the result. And usually they do not. To do this, we will "hold still" the other Effectiveness factors by simply letting P = 100, D = 1.0, and U = 1.0, so that Reliability becomes a measure of Effectiveness. Then:

$$\text{Cost-Effectiveness } C\text{-}E_r = \frac{100R}{C_a + C_u}$$

Now we can examine the inherent effect of Reliability upon these costs C_a and C_u, and hence upon Cost-Effectiveness. We will do this first at the system level, then getting right down to specific shipboard equipment experience data.

3.2 TYPICAL SYSTEM

Now what we want to know is "How much reliability and maintainability is worth the expenditure?" Since the need for maintainability is a function of reliability, it becomes logical to see what happens to Cost-Effectiveness as reliability is varied, for various values of maintainability. So we will use a reliability scale across the bottom of Figure 26-17. For visualization, as well as simpler arithmetic, we will use system Mean Time Between Failures, or MTBF. And by using "Relative" MTBF = 1 for state-of-the-art reliability achievable without extra Acquisition Cost, we have a scale that permits visualization of reliability improvement needed.

Using the data from an actual system, graph E shows that reliability would increase if MTBF were increased beyond state of the art. For this particular system, Effectiveness is actually proportional to the product AR of Availability and Reliability, so taking a typical Maintainability (MTTR) into account results in the curve AR. And since we have "fixed" Performance Capability, Delivery Effectiveness, and Utilization, this curve AR becomes a measure of the Effectiveness E of the system.

Now referring to the Total Cost graph C_t we note that the Acquisition Cost of the system rises with required MTBF. Just how much will be discussed later, but it commonly results from tighter engineering, supplier, and manufacturing controls, and from design for higher reliability as discussed in chapter 13.

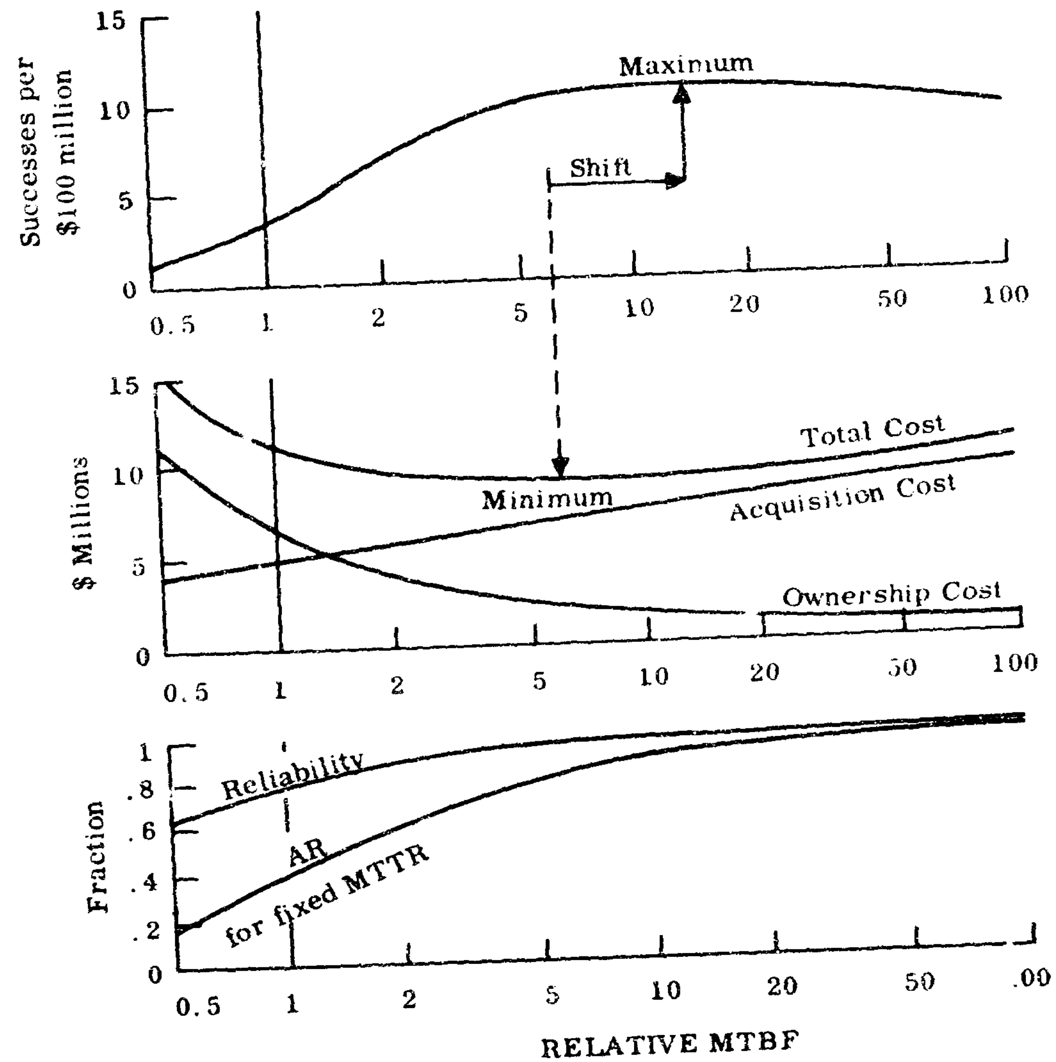
As MTBF is increased, the resultant Ownership Cost drops about as shown. This results from simple reduction of the number of

SYSTEM COST-EFFECTIVENESS

COST-EFFECTIVENESS
E/C_t

TOTAL COST
C_t

EFFECTIVENESS
E



failures and hence corrective maintenance manpower, facilities, and inventory to take care of them. Then we can add these two cost curves to obtain the Total Cost curve, which shows a minimum at relative MTBF of 6. The curve says that spending an additional $1.7 million for Acquisition would have saved $4.2 million in Ownership Cost, for a net $2.5 million saving. At the same time the Effectiveness (i.e., AR) would rise from 40 to 85%, a ratio of about 2-to-1.

But this is not the optimum reliability! In the Cost-Effectiveness graph E/C_t we have plotted the ratio of Effectiveness to Total Cost, taken directly from the two graphs below, and find the peak is at relative MTBF of about 14. The AR curve has shifted the peak to higher MTBF. This is very typical. This curve says it's even better to spend $2.3 million on Acquisition, saving $4.5 million in Ownership, netting $2.2 million savings, but getting 2.9 times as much Effectiveness. These curves are built on the data from a very real vehicle system, only the Acquisition Cost line being estimated.

But what about Maintainability? Suppose we invest in design for one tenth the Mean Time to Restore. In Figure 26-19 the solid curves are identical to Figure 26-17. The dashed lines show the predicted result for MTTR ÷ 10. Note that (a) the cost-effectiveness is about doubled, compared to almost 3-to-1 for MTBF × 10, (b) the best MTBF is then ×5 instead of ×14, and (c) the achievable cost-effectiveness is then less than if MTTR were left alone.

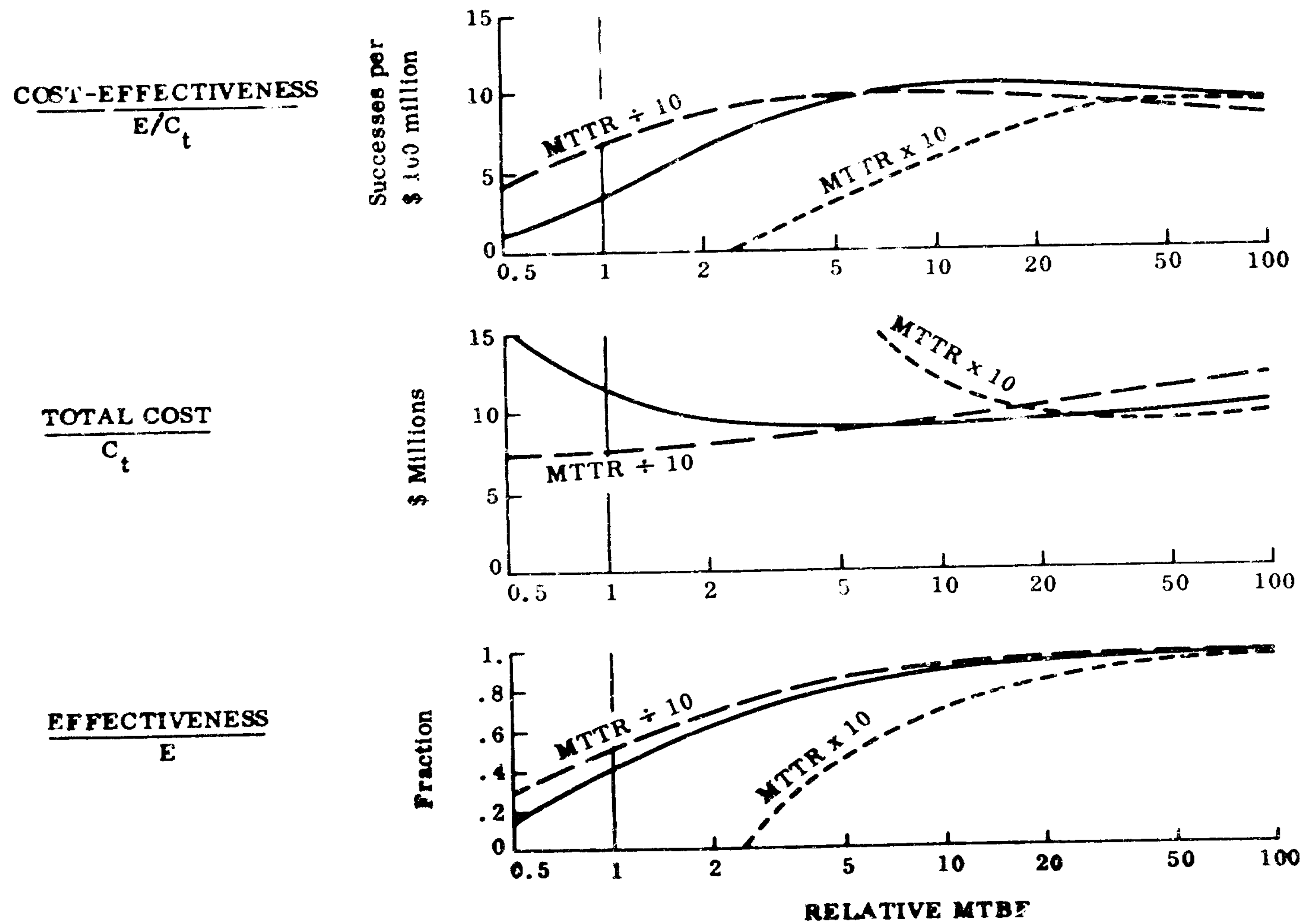
Thus while these conclusions apply only to this specific system, it is clear that a family of such curves can show the optimum combination of MTBF and MTTR for any system.

3.3 TYPICAL COMPONENTS

Now let's turn to hardware equipment and parts in Figure 26-20. This figure is identical to figure 26-17 except that we have carried the relative MTBF scale at the bottom to the much higher values associated with component MTBF. They are so very much higher than the typical Mission Time and typical MTTR, that Reliability and AR are practically 100%.

Again these curves are from real equipment and this time the Acquisition Cost data were meticulously calculated for 3 points, and one of these confirmed. We note the identical Total Cost situation, but this time the peak of Cost-Effectiveness coincides with minimum Total Cost, because the Effectiveness curve is flat.

SYSTEM COST-EFFECTIVENESS VS MTTR

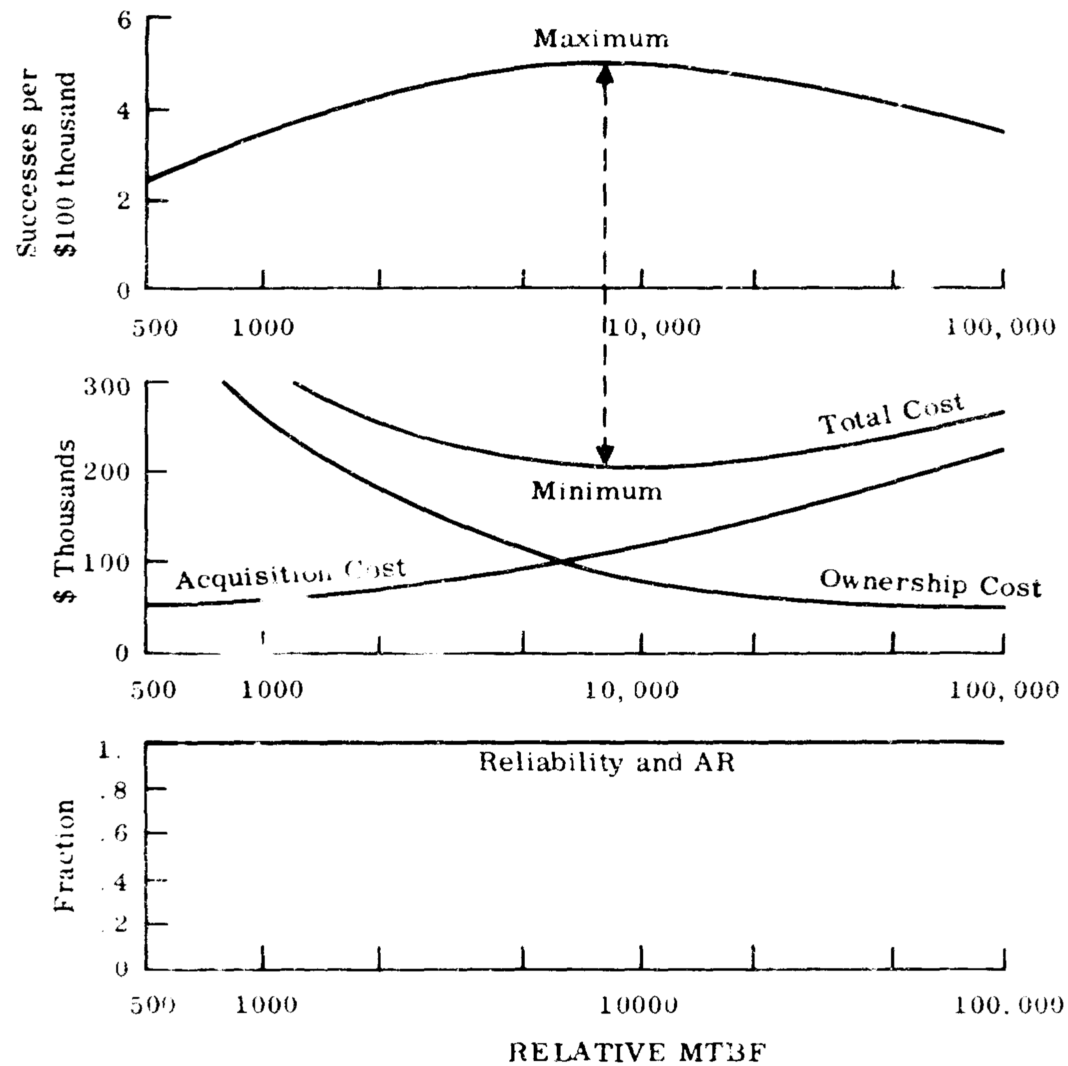


COMPONENT COST-EFFECTIVENESS

COST-EFFECTIVENESS
E/C_t

TOTAL COST
C_t

EFFECTIVENESS
E



This occurs quite commonly for equipment and parts cost-effectiveness analysis, so there is seldom need to plot the ratio to locate optimum MTBF.

Thus we see that it may be economic nonsense to insist on "maximum" reliability. There is always a value of MTBF for a part, equipment, or system beyond which there is diminishing advantage. But note too that these Cost-Effectiveness and Total Cost curves tend to be quite broad, which means that it costs very little more to get 2 or 3 times the "optimum" MTBF if it is that significant to the mission.

3.4 OTHER TECHNIQUES

Although cost-effectiveness analysis seems by far the most powerful and useful tool that can be used to determine optimum reliability and maintainability, it is by no means the only one that can be used. There have been a number of attacks on this tradeoff problem. A few are cited herewith for reference purposes, for those who wish to "dig deeper."

An excellent review of the engineering tradeoffs is given in reference (11). Under "internal tradeoffs" it covers system performance tradeoff, reliability/cost tradeoff, reliability/schedule tradeoff, reliability/confidence tradeoff, and combined tradeoffs. It also discusses external tradeoffs and tradeoffs as program management aids.

When Availability has more significance than Reliability, as for many shipboard situations, a Performance/Availability/Cost block diagram can be constructed (12). Each block, including redundancy, is assigned a Performance, Availability and cost. The binomial theorem is used to calculate the probability of each block combination being in service. Then the effect of 1% Availability improvement of each block is calculated, to determine the most economical opportunities for improvement. This corresponds to study of the slopes of Figures 26-17, 26-19, and 26-20.

Total cost can be plotted against development time, using a curve for each design alternative having fixed Reliability or Availability (13 p.18).

Standardization of parts, equipment, and systems not only reduces cost but increases reliability through greater refinement of the same design. The tradeoff is between performance, reliability, and cost (14).

The BuShips Design Work Study Program (15 p.4) provides a "logical, systematic, fact-finding method of determining what needs to be done, how it should be done, and who should do it," in finding more economical systems of men and equipment.

System reliability vs. weight or volume tradeoff curves for various levels of redundancy may be used (16 p.64,67).

Industrial main boiler forced outage (unavilability) of 1% is said to require 4 to 5% increase of reserve capacity to conserve the same system reliability (18). Variations of this are given in reference (19) and discussed in reference (37,p.135).

3.5 PRACTICAL ANALYSIS

It is seldom difficult to write fairly simple equations (ordinary algebra) expressing (a) Effectiveness in terms of its interrelated factors, (b) each Effectiveness factor contribution to Total Cost, and then (c) the expression for Effectiveness/Cost ratio. This can and always should be done as a prime design guide for tradeoff decisions.

Cost-effectiveness analysis of a proposed alternative or design change, relative to a first alternative or current design, is very useful. By evaluating the curve slopes in Figures 26-17,26-19, and 26-20 rather than their absolute values, the dependency upon uncertain absolute data is greatly reduced and confidence in the result can be very good. See also reference (20,p.21,22).

Faced with a choice between redundancy and component improvement to improve reliability, reference (26) provides an excellent analytical tradeoff approach based on cost-effectiveness. It incidentally concludes that (a) the optimum strategy can be improvement of the strongest instead of the weakest reliability link, (b) large sums spent on component development may never achieve the minimal system effectiveness, and (c) redundant major components can easily achieve the minimal system effectiveness.

Reliability and Maintainability can be made to substitute for each other to some degree, over a wide range of Availability (22,33 p.8-23). Cost-effectiveness analysis can be used to make the tradeoff economically optimum.

Value Engineering techniques (23,24) are called out in the Guide for the Preparation of TDP Dependability Plans (25, p.16). The identical techniques can be used with cost-effectiveness (instead of simple Acquisition cost) criteria to achieve optimum reliability and maintainability, as discussed in chapter 13, section 1.1.

4. EXAMPLES

With this background we can now get into some specific examples and data. Such published data is very scarce. We have scoured the literature and found a few marine equipment examples and several naval electronic equipment examples. But most of the needed data can be obtained by going after it. And it is becoming painfully obvious that we must establish channels to get, classify, collate, and distribute it fairly automatically.

4.1 PUMP TOTAL COST STUDY

An Allis-Chalmers study (27) of their 5" x 4" KSK and SK pumps, used by the Navy, was undertaken for pumps sold between 1953 and 1962. Failure and operating time information on 117 Navy-owned pumps was obtained from aircraft carriers, the NAVSHIP-527 Machinery History Card, and the NAVSHIPS-3621 Reports of Equipment Failure. Also 104 responses were obtained from commercial customers. Cost information was obtained from Allis-Chalmers, adjusted to the base year 1954, and normalized for proprietary reasons. Very detailed analysis is given in the reference.

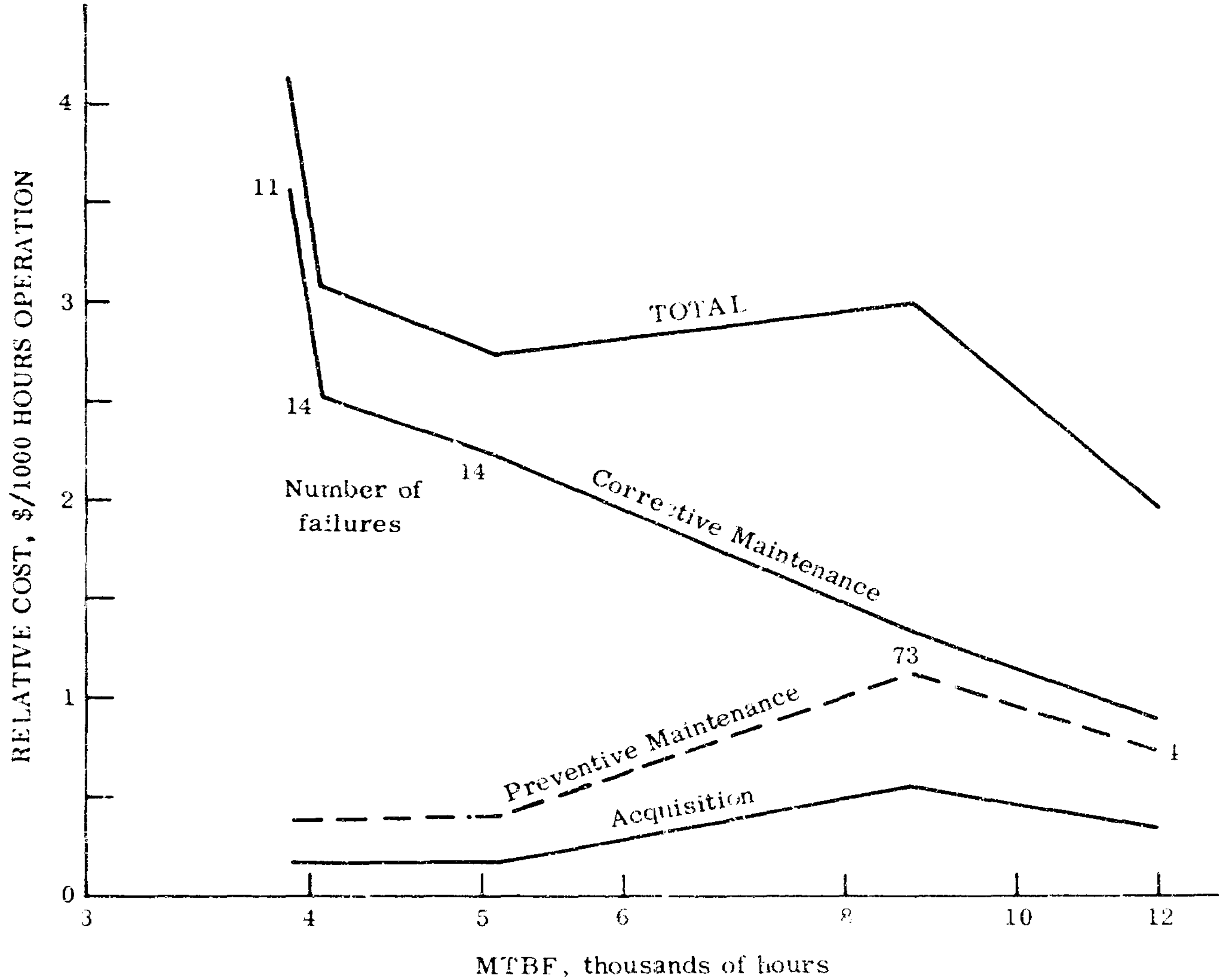
Referring to Figure 26-24, all pumps were classified by design similarity into groups. The Acquisition curve, as a function of MTBF of each group, is the manufacturers normalized selling price, prorating assumed 30,000-hour life to the fraction of price for 1000 hours. It includes specifications, R&D, product engineering, engineering changes, new patterns, small tools, burden, shipping expense, warranty costs, and 7% profit.

Preventive Maintenance costs for parts and labor were calculated on the assumption that standard recommendations were followed.

Corrective Maintenance costs for parts and labor were calculated from the accumulated failure data, all of which were factored to common seawater operation. The figures alonside the curve show number of group failures on which the point is based, as an indication of confidence level surrounding the MTBF value. Note the large number of 73 for one group.

The Total curve adds the three below it. Clearly the trend is reduced cost for higher MTBF. We can also tenatively conclude that optimum MTBF is off the chart at still higher MTBF. In any event it is apparent that increased Acquisition Cost of high reliability, within this range at least, pays off several-fold in reduced Total cost.

PUMP TOTAL COST



If we know the Mean Time to Restore, which the reference does not give, we could calculate pump Availability. Then we could draw a Cost-Effectiveness curve using the ratio of Availability to Total Cost. But since pump Availability is probably 99% or better, the Cost-Effectiveness curve would be essentially a reciprocal of the Total Cost curve, leading to identical conclusions. Thus we see that this step is useful only when MTTR or Mission Time are substantial in relation to MTBF.

4.2 TURBINE STOP-VALVE TOTAL COST

The following example is a projection of existing steam system design to conceptual redundant design alternatives. It uses existing valve MTBF and cost data to predict the achievable MTBF and cost of alternative untried configurations. It is not verification of achieved Cost-Effectiveness, but does illustrate the use of cost-effectiveness analysis in design to obtain the optimum reliability.

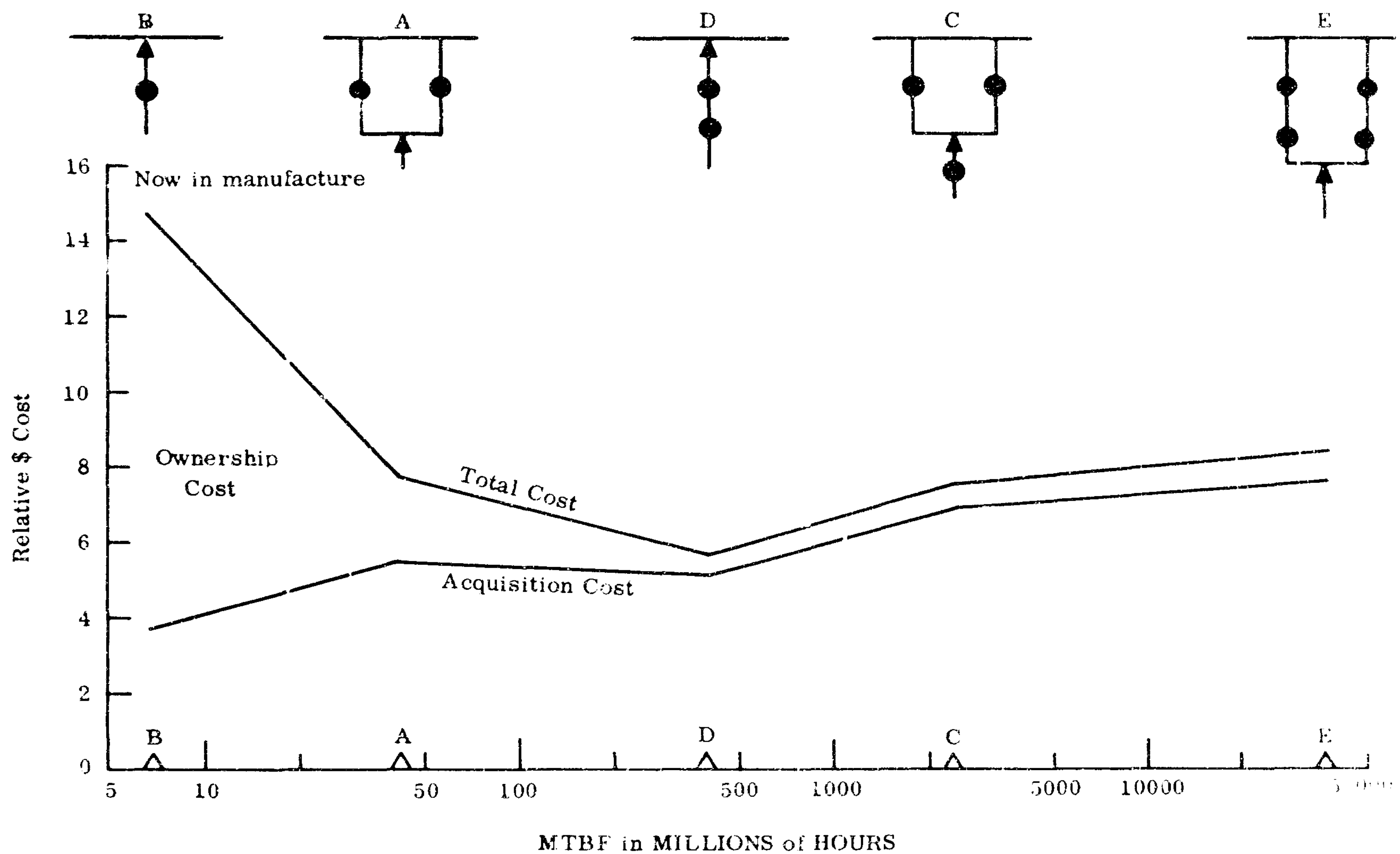
The stop valve of a public utility turbo-generator (29) is controlled by the overspeed governor, and is used only when it exceeds speed by 10%. The valve is expected to close completely within 0.3 seconds when the generator loses its load, or for other reasons. Failure to close may cause "blowing" of the turbogenerator, and consequently destruction of the equipment.

Five stop valve arrangements are shown at the top of Figure 26-26, the horizontal lines indicating the input manifold to the governing valves, which in turn feed the turbine. In system A the failure of either valve to close will fail to stop steam flow. However either valve may be exercised in periods of light load, (say every week) to insure satisfactory operation, because the other will sustain turbine speed. In system B the valve may not be exercised until shutdown (say every 4 months). Thus the shorter "mission" time (1 week) results in higher reliability for A than b, even though failure of either valve is system failure.

Using the data collected on valves with operating time totalling over 3 million hours, analyses of the reliability of 5 such stop valve arrangements has been computed, as indicated at ABCDE on the horizontal scale.

Acquisition Costs for A and B were obtained from existing arrange-

STOP-VALVE SYSTEM COSTS



ments, C, D & E being computed using the component costs of valves, piping supports, equalizing passages, etc. For proprietary reasons the cost results are normalized using an arbitrary but fixed factor.

Ownership Costs include Maintenance and Consequence-of-failure costs. Maintenance includes scheduled preventive maintenance every 3 years, as well as unscheduled corrective maintenance based upon separate operational and non-operational failure rates and the reconditioning and restoration-to-service cost each time.

Consequence Costs occur when stop valve failure has resulted in turbo-generator damage beyond repair. For a 100-MW unit it may take 2 years to get another unless one was being manufactured, during which time an older less-efficient one may be used or power bought from another utility. Such costs were estimated at 150% of the turbo-generator Acquisition cost, plus 5% of original dollar output at 75% capacity. All costs were calculated over 30-year life. Similar estimates can be made for shipboard failure in terms of the manpower and depreciation cost for added mission time at reduced performance.

Total Cost is then the sum of Acquisition and Ownership costs, as plotted in Figure 26-26. It is clear that, of these alternatives, minimum Acquisition Cost at B does not provide minimum Total Cost. It is also clear that there is an optimum stop-valve system reliability, achievable via system D. Higher reliability would be less economical.

The Effectiveness of a system is its accomplishment of objectives, which has not been taken into account in the above. But even if we assume the worst possible Reliability (MTBF = 6.8×10^6 hours) and Maintainability (inability to get a turbo-generator replacement for two years or 17500 hours) the Availability is $6.8 \times 10^6/(6.8 \times 10^6 + 17500$ hours) or 99.3%. For the utility this is a measure of Effectiveness, since Performance Capability, Delivery, and Utilization are unchanged. If we plotted Cost-Effectiveness (the ratio of Effectiveness to Total Cost) against MTBF in the above example we would gain no further insight.

For a Navy ship it is not uncommon to have a fourth 750 KW turbo-generator for reliability insurance, where three can actually handle peak loads, and two can nicely handle normal loads. Thus Effectiveness is not degraded by one failure. But the question does arise whether the added reliability of the fourth is worth its cost. An analysis similar to the above could be conducted, taking battle environment into account as a potential cause of failure.

4.3 GUIDANCE COMPUTER

Early in 1959 IBM was awarded a contract for a missile guidance computer (30) with an MTBF requirement 50 times that being realized in an operational bombing navigational system. This requirement was met on schedule because the reliability activities were a prime factor in R&D planning.

Three different proposals were generated, each for a different MTBF level. The anticipated costs for these are shown in Figure 26-29, in which cost and MTBF have been normalized for proprietary and security reasons. On the horizontal scale, unity is the MTBF achievable with a "normal" reliability program. The other two proposals were for 4 and 10 times this. The decision was for 4, which is 50 times the 0.08 previously obtained. The actual result obtained was 6.8, via the detailed techniques detailed in the reference.

Figure 26-30 shows the actual reliability program costs as percent of contractors program cost. Such figures are commonly used as indices of reliability effort, but are also very tricky because of the wide disparity in meaning of the words among contractors. Yet "reliability programs" have ranged 5 to 15%, sometimes higher. The reference contains descriptions of the detailed activities.

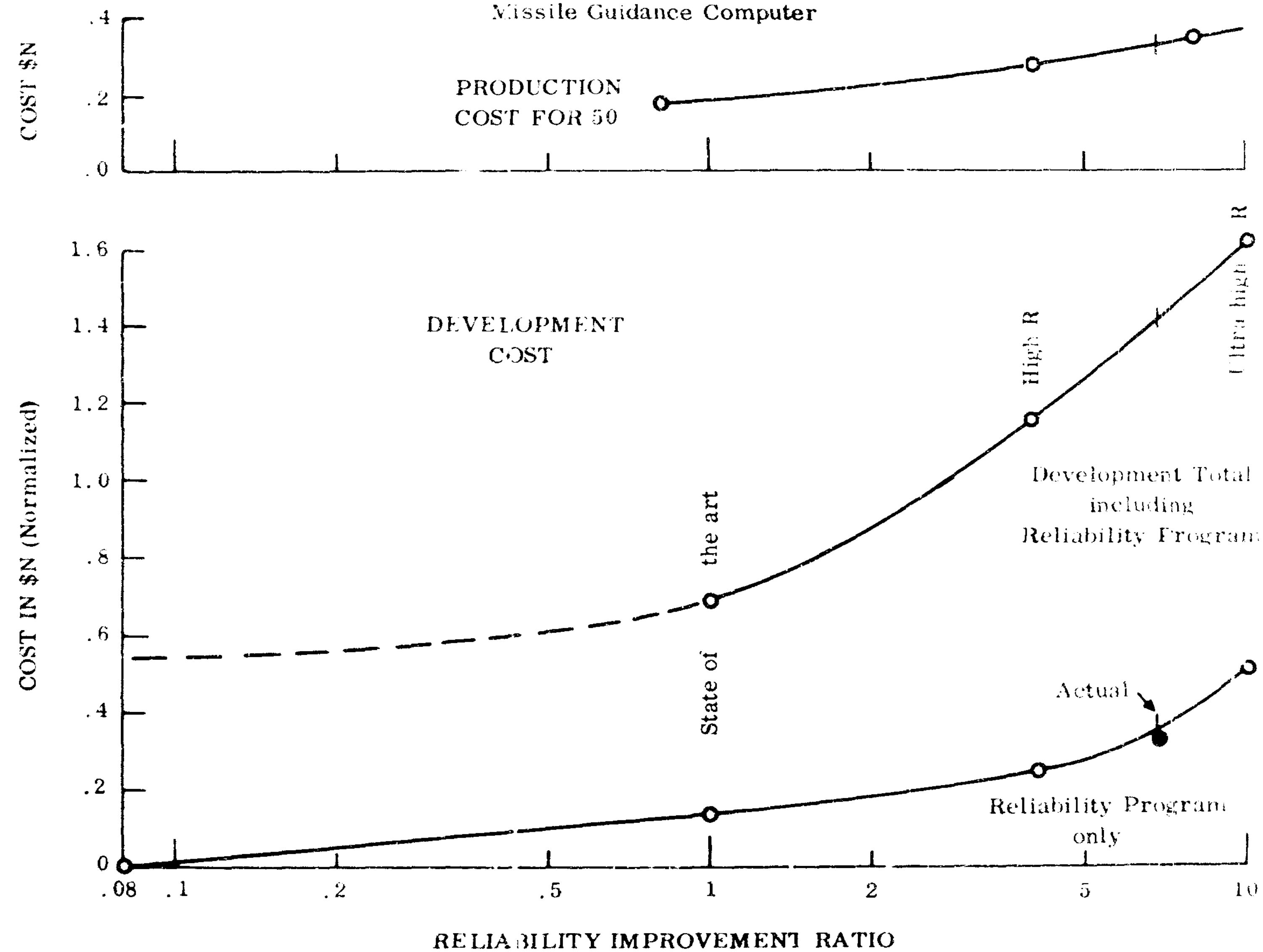
The reference then gives detailed attention to operational cost breakdown for a quantity of 50 computers. The Figure 26-31 "Production and Operating" cost curve combines these quantity-related costs. The "Development" cost curve is repeated, so that the two may be added to get the "Total" cost curve. It will be seen that minimum total cost occurs at around 3 to 4 times MTBF improvement, while the actual turned out 6.8 for somewhat higher cost.

In the absence of actual MTBF and mission time data, we can compute the reliability for mission times of 1, 0.1, and 0.01 of the state-of-the-art MTBF of 1. If Performance Capability, Delivery Effectiveness, and Utilization are unity, and there is no opportunity for maintenance, then Effectiveness is measured by Reliability. So we can divide Reliability by Total Cost to get Cost-Effectiveness. We see that optimum MTBF has moved up slightly for mission time of 0.1, but quite significantly for 1.0 mission time.

For 1.0 mission time we see that optimum MTBF improvement is about 7 times, which is what the program actually achieved. Had

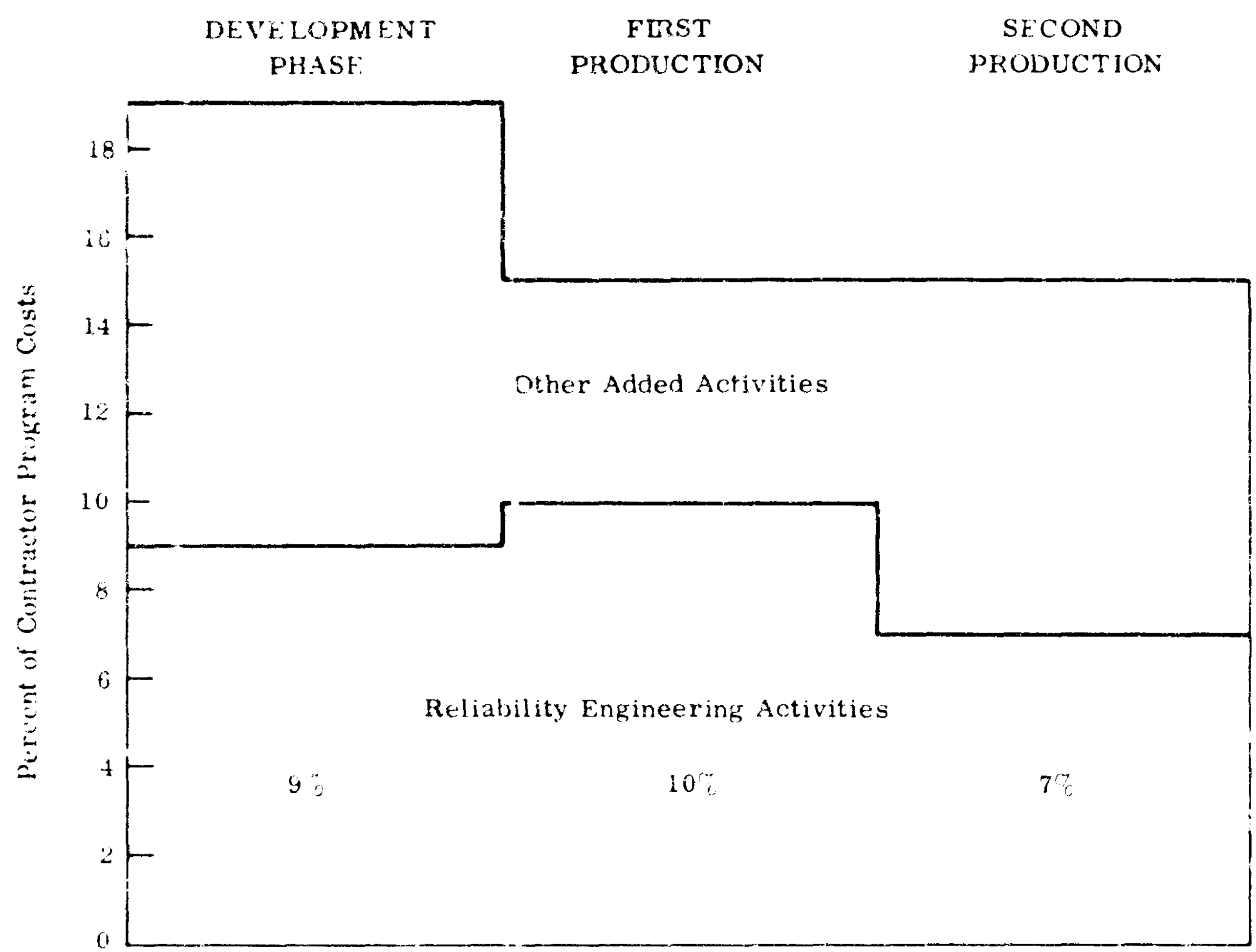
ACQUISITION COSTS

Missile Guidance Computer



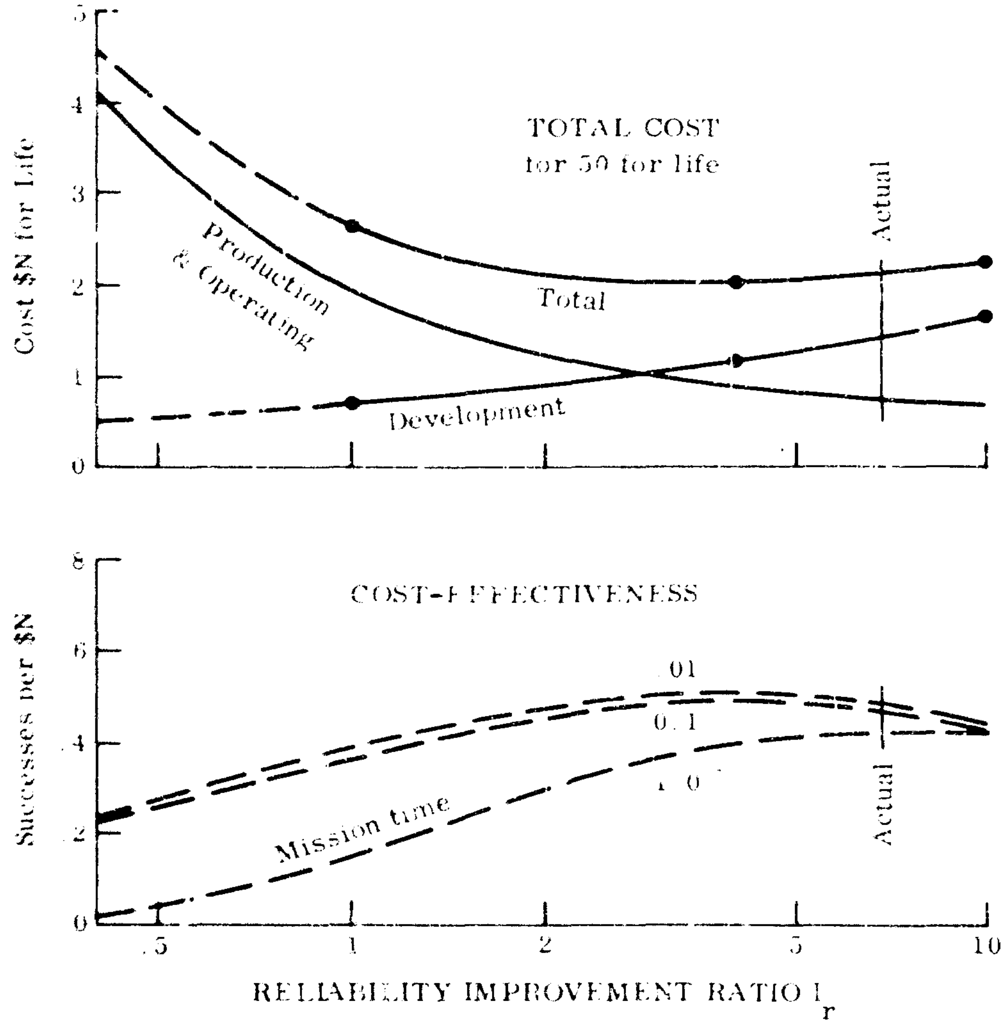
RELIABILITY IN ACQUISITION COSTS

Missi e Guidance Computer



TOTAL COST-EFFECTIVENESS

Missile Guidance Computer



we looked only at minimum Total Cost, we would have concluded that about 3.5 was optimum, and that the actual achievement was excessive.

4.4 POLARIS GUIDANCE COMPUTER MAINTENANCE COST

A Study (31) was undertaken of the best overall maintenance strategy for periodically-checked equipment which cannot be re-supplied in its operational environment, such as a submarine cruise. Relatively little time was spent on data gathering, so that the results should be regarded as illustrative more than conclusive.

The analytical model considers not only "out of pocket" costs such as manpower, repair facilities, test equipment, etc., but also "real" costs such as those due to shortage of replacement parts and modules, and submarine space. The inclusion of shortage cost prevents minimization of cost at the expense of operational Effectiveness. Costs were computed vs. MTBF on the basis of four possible maintenance policies, the fifth below being essentially the same as the fourth:

1. Discard and salvage
2. Repair on the submarine
3. Repair on the tender
4. Repair at the factory
5. Repair at the Naval Weapons Annex

The cost factors considered were:

1. Inventory support costs
2. Parts for repair
3. Test and repair equipment and facilities
4. Submarine space
5. Restoration manpower
6. Transportation, handling and packaging.

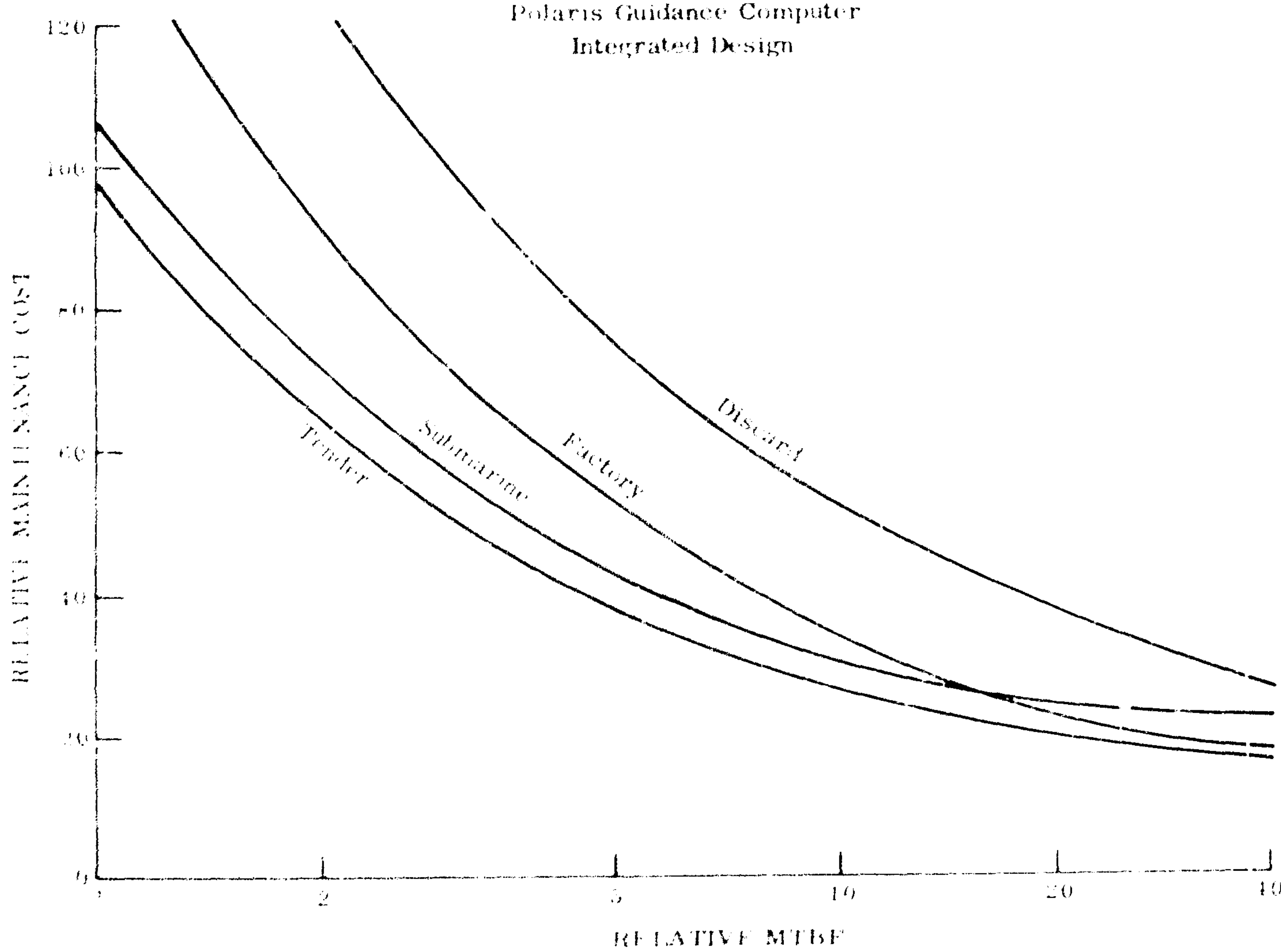
Figure 26-33 shows the effect of maintenance locale upon Maintenance (therefore Ownership) Cost, the "Discard" curve being the cost of replacing without repair of failed units. Not surprisingly, the discard of an entire computer is not economical except at very high MTBF. Repair on the tender turns out best, with submarine a close second.

A comparison between integrated and plug-in computer design in Figure 26-34, assuming tender maintenance for both, shows the great importance of this design decision. For unity relative

MAINTENANCE COST VS MTBF

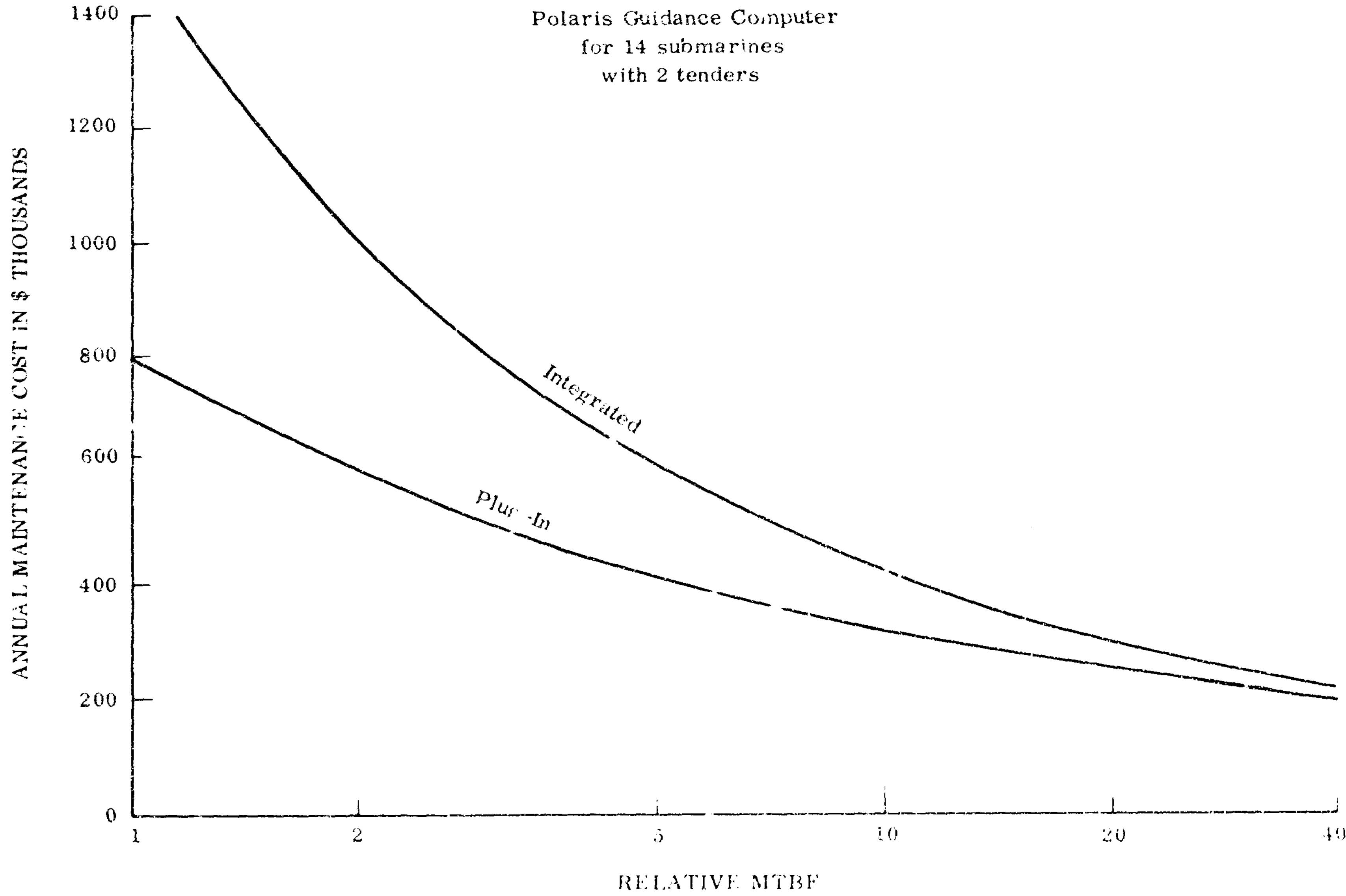
Polaris Guidance Computer

Integrated Design



ANNUAL TENDER MAINTENANCE COST

Polaris Guidance Computer
for 14 submarines
with 2 tenders



MTBF (which may be state of the art) the plug-in design saves $800,000 annually, mainly through reduction of required inventories. On the other hand plug-in designs tend to have higher Acquisition Cost (for design and manufacture) and because of their higher number of connections tend to have lower MTBF. But $800,000 would buy a 32-man continuous design effort to overcome inherent plug-in reliability problems and achieve order-of-magnitude MTBF improvement.

5. RELIABILITY ACQUISITION COST

We have discussed at some length an analytical approach to design tradeoffs. But like most analytical techniques, it requires meaningful data inputs in order to draw meaningful conclusions. This section discusses one very important input, Acquisition Cost data, perhaps the most difficult.

5.1 ACQUISITION COST ELEMENTS

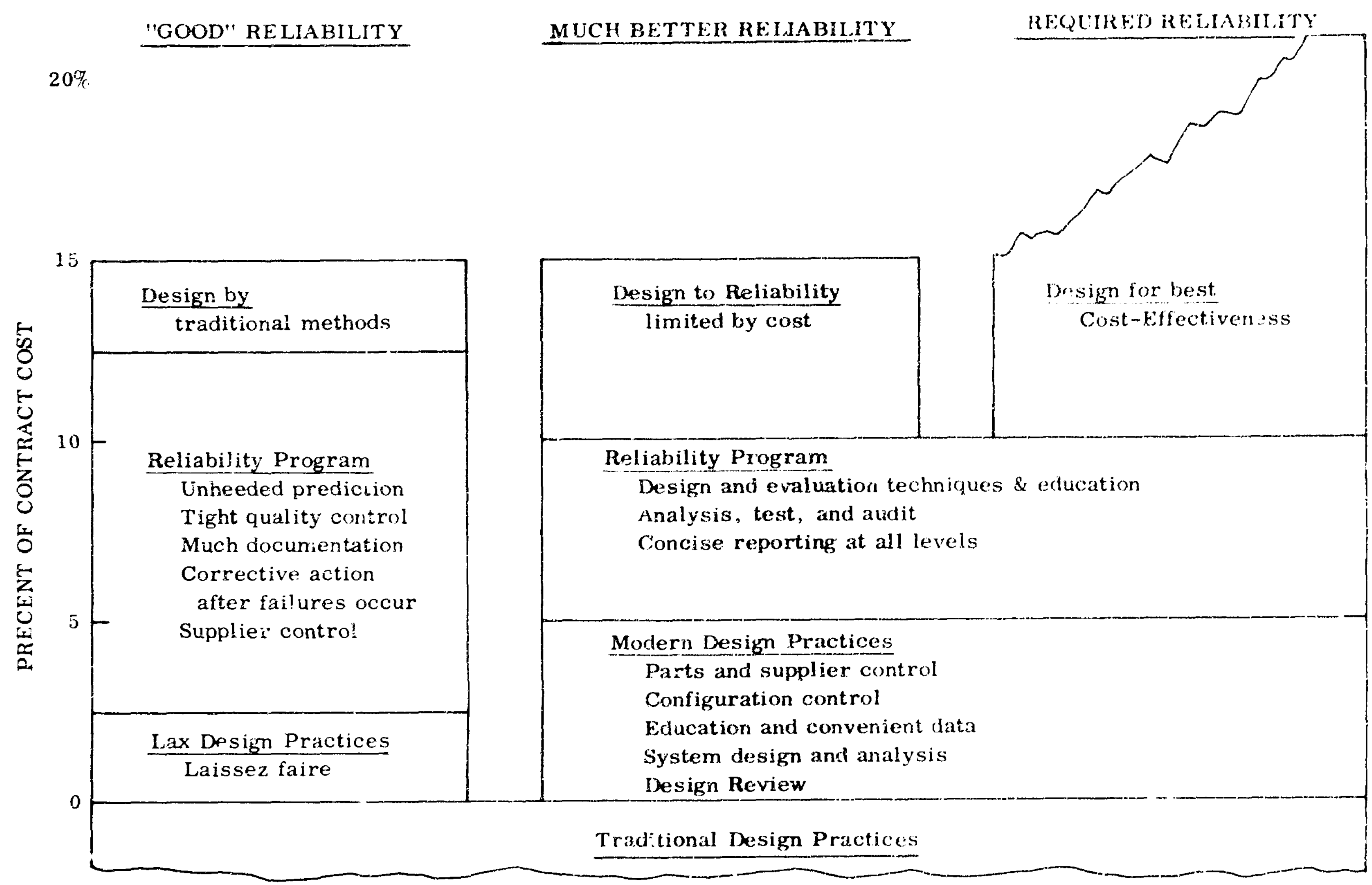
The cost of achieving reliability is very real, but such cost data is very scarce. To understand the sources of such cost we can consider four broad categories as illustrated in Figure 26-36.

1. Traditional design practices where the design engineer draws upon his personal experience, uses much intuitive judgment, and conducts some analysis. The product is built, its failures are analysed, it is redesigned, and at least several such complete cycles are required before the product achieves maturity. (In shipbuilding many such cycles have long since occurred, resulting in standard "margin" practices) But today we often need adequate reliability the first time in designs for which no experience is available, and cannot tolerate the time and cost of recycling.

2. Modern design practices are employed, using standard parts control, supplier control, configuration control, education in new technologies, data dissemination in convenient form, system design and analysis, stress/strength analysis, and design review. These practices get moderately good reliability in areas where there is little prior experience, and are expected as part of any substantial contract without additional cost.

3. Reliability programs add reliability program planning, "reliable" design and reliability evaluation techniques, reliability education, quantitative reliability requirements on

RELIABILITY ACQUISITION COST



designers and suppliers, analysis, test and audit of design, stress time and failure recording and data dissemination, failure analysis, corrective action control, and the use of MIL R 38100 "Established Reliability" parts. Such programs get steady reliability growth, typically 2-to-1 MTBF improvement in 4 years.

4. Design to specified reliability does not mean design to a "goal", merely using "modern design practices" and a "reliability program" to get the "best possible" reliability within contracted cost.

   It does mean conscious design to a specified quantitative MTBF or % reliability, no more and no less, which is rarely done. It involves simplification techniques, standardization, parts selection and application, stress/strength design, tolerance evaluation, failure rate prediction, human engineering, failure cause and effect avoidance, preventive maintenance provision, producibility, supplier evaluation and control, evaluation tests, local environment control, failure prediction devices, component integration, redundancy, and parts improvement. See chapter 13.

   Such techniques can often get one or more orders of magnitude reliability improvement to satisfy the actual need. They can make some of the tight "control" elements in 3 above unnecessary.

Most contractors do not have real "Reliability Programs", in the above sense, but the good ones utilize the above Traditional and Modern practices. Of the contractors who do have "reliability programs", almost all have some fraction or all of the above reliability program elements. Such reliability programs generally cost 5 to 10% of the contract design cost, excluding factory quality assurance, inspection, and test.

Design to specified reliability has been undertaken by relatively few contractors. The techniques are spotty, not really shaken down, and the reliability required by such specification is seldom achieved due to contractual cost constraints. Yet the techniques are imperative for many of our projected long-life applications like submarine missions, underwater dormant weapons, space probes, etc. They may be costly, yet perhaps no more so than the reliability "control" techniques, some of which would then not be needed. But the payoff in maintenance cost reduction above justifies much more than is spent today.

Design for best cost-effectiveness is design for whatever value of Reliability and Maintainability is best considering Total Cost. It will generally cost more for Acquisition, but Ownership Cost savings result in a net Total Cost reduction.

Figure 26-35 thus attempts to show that even though "good" reliability is being obtained with and without heavy reliability "control" programs, such programs are often merely a crutch for obsolete or immature engineering practices. When this is the case, it should be possible to get much better reliability through better engineering practices, and smaller reliability programs, without increasing the Acquisition Cost. But to actually get the optimal reliability for best cost-effectiveness, still higher Acquisition Cost may be needed.

5.2 ACQUISITION COST HISTORY

In Figure 26-39 we have converted several items of Acquisition-Cost vs. reliability data to a common basis for comparison. Relative MTBF of unity indicates state of the art. Relative $ Cost of unity is the Acquisition Cost (purchase price) at state of the art. More details on the background for each curve are obtainable from the references indicated below.

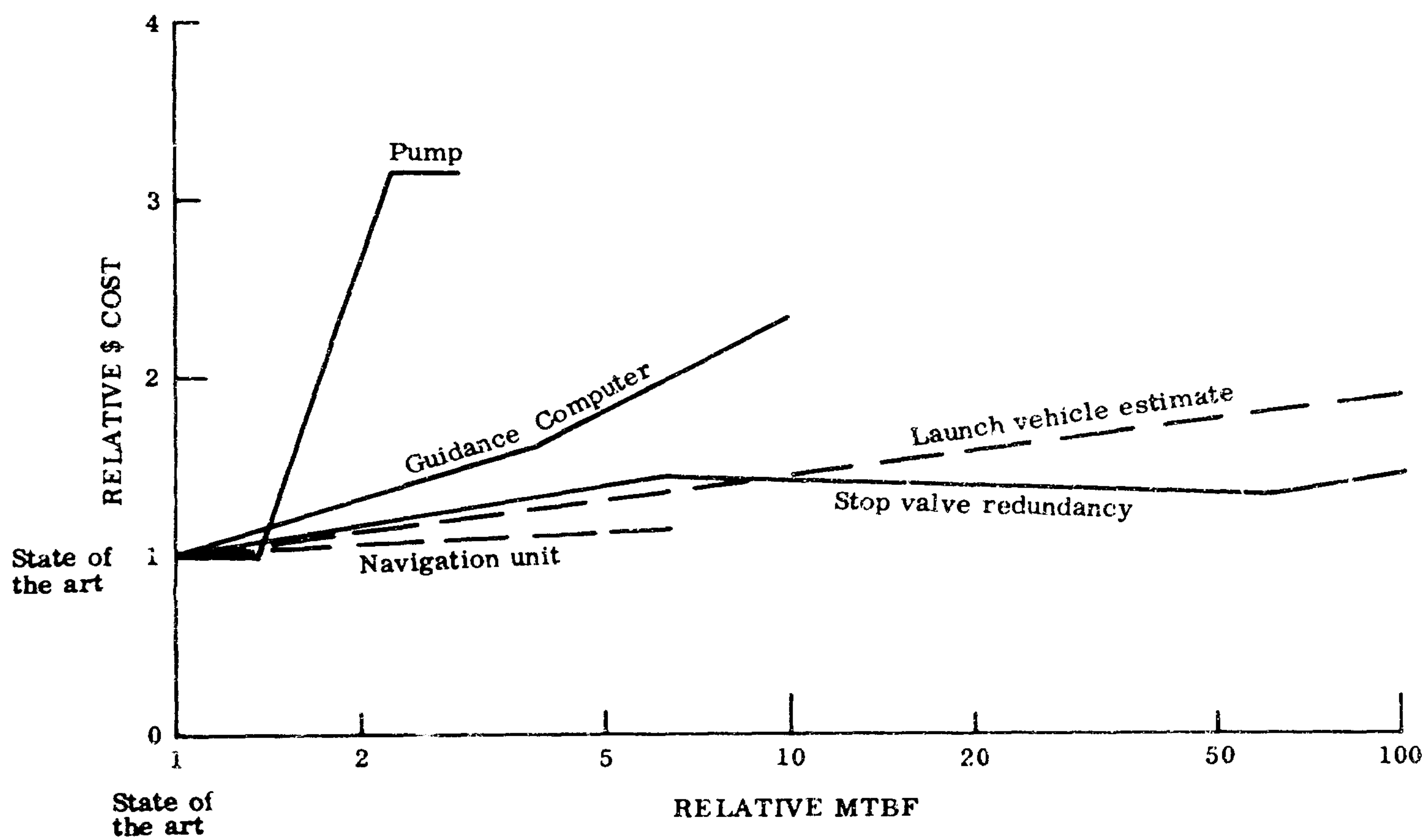
The Pump curve results from merely historical information (27) over nine years, without benefit of a reliability program as outlined above. The Guidance Computer curve comes from a detailed plan of three alternative approaches (30) from light to heavy reliability programs. The Stop Valve Redundancy curve actually results from redundant use (29) of one to four identical valves in different configurations, an excellent example of this technique.

The Navigation Unit curve is based on a factual comparison (32,33) of total cost of redesign and production to original cost of design and production, which was 10% cheaper for 6-to-1 MTBF improvement. But in the absence of design cost data we have assumed that original design cost 25% of the total, so that fresh design and production would have cost 15% more than the original design and production.

The Launch Vehicle Estimate curve resulted from a consideration (10) of the limits between which it could possibly range, then trial, intuitive judgment, and correction of several alternatives.

5.3 ACQUISITION COST DATA SOURCES

RELIABILITY ACQUISITION COST



As indicated above, data relating design and manufacturing cost to MTBF achieved is very scarce. The data presented above resulted from several weeks research of the past few years' reliability conference and periodical literature, with emphasis on Navy material. Certainly more could be turned up with further detailed research.

When adequate component cost/MTBF data cannot be found in the literature, the following approaches will often get it:

1. Informal request of manufacturer

2. Formal request for manufacturers quotation at several MTBF levels.

3. Informal request of contractors who have used the component.

4. Bureau procurement records for cost and maintenance records for MTBF.

When direct cost/MTBF data is not obtainable, one must resort to indirect approaches. Each kind of design and manufacture presents its own problems, but generally the analysis approaches are:

1. Gross evaluation of cost/MTBF achieved by very similar or identical sequential programs.

2. Synthesis of incremental task costs to achieve various MTBF levels.

3. Calculation of cost and MTBF achievable with various redundancy configurations of components of known cost and MTBF. This is a "worst case" cost which actual design should reduce.

4. Analysis of cost and MTBF as related to a complexity common denominator, using data for real "design for reliability" programs.

5. Analysis of manufacturers maintenance schedule and spare parts recommendations.

6. OWNERSHIP COST

This element of Total Cost is the aggregate of all costs to the user after the system is first made operational, and incurred throughout its useful life. It is also commonly called "user" cost, and sometimes "operational" cost. It is most of the iceberg.

The Operational Cost elements (training, operator salaries and facilities, etc., for operators) are fairly easily predictable from study of the system design itself.

The Maintenance Cost elements (preventive and corrective maintenance, maintenance personnel salaries and facilities, spare parts, logistics, etc.) typically constitute the bulk of ownership cost; they depend primarily upon reliability (MTBF) and to a lesser extent upon maintainability (MTTR).

The Consequence Cost elements (damage to or loss of equipment, personnel, or other resources external to the system as a result of its failure) obviously depend directly upon how the system is used, and upon its reliability (MTBF) and safety. But Consequence Costs and Maintenance Costs are almost the sole criteria of the importance of reliability, and hence justification for its achievement.

Ownership Cost data must come from the owner or user, as opposed to Acquisition Cost data from the Contractor or manufacturer. But it is just as scarce, for different reason. While a growing amount of field maintenance data is being collected, it is as yet by no means adequate for many specific Ownership Cost analyses. The analyst must resort to indirect methods based on available data.

NAVSHIPS 94324 Maintainability Design Criteria Handbook (34) provides detailed maintenance times for each increment of electronic maintenance, as well as skill levels available. These can be converted to direct maintenance costs.

The Machinery History Card, NAVSHIPS 527 (27 p.175) is an important source of maintenance manpower data. Reports of Equipment Failure NAVSHIPS 3621 (27 p.176) also provide maintenance manpower data. Shipyard repair records (35 p.344) contain much maintenance cost data.

Many papers have presented methods of obtaining or estimating ownership costs. Each kind of system design and utilization presents its own problems, but generally the analysis approaches are:

1. Gross evaluation of cost/MTBF/MTTR achieved by very similar or identical sequential programs.

2. Synthesis of incremental task costs resulting from various MTBF or MTTR levels and environments.

3. Straightforward collection of user data during operation, which of course is too late for the current design but may be quite valuable for the next.

7. <u>OPPORTUNITIES FOR IMPROVEMENT</u>

The principles of cost-effectiveness analysis are <u>not</u> being applied to design except in very rare instances. But this does not detract from their significance and the imperative need to apply them as quickly as we can. Mr. McNamara has directed their broad application, and Messrs. Hitch, Secretary Longstreet, and Rear Admiral Fawkes have recommended their use wherever feasible.

This section addresses most of the reasons that the principles have not yet been applied, and translates each to deliberately concise statements of programs that the Bureau could and should consider to initiate action on cost-effectiveness analysis.

<u>7.1 PROPOSAL REQUIREMENTS</u>

Require selected prospective contractors to include in their proposals an analysis of total costs and effectiveness vs. a range of MTBF and MTTR.

<u>7.2 COST-EFFECTIVENESS STUDY</u>

When the problem is too complex for meaningful analysis in proposals, issue advance study contracts to say three experienced contractors, each to conduct a cost-effectiveness study based on his own development and manufacturing costs. This will show what MTBF and MTTR is achievable, and tell much about the contractors reliability and maintainability capability (27,p.219,item 2). Recently the Bureau has been directed by DOD to do this on specific programs.

<u>7.3 ACQUISITION COST DATA IN CONTRACTS</u>

Require contractors to provide development and manufacturing cost data by principal component, whether or not it may also be needed, by department. (27 p.214 item 5; p.215 item 1b). Then relate to actually achieved MTBF and MTTR.

<u>7.4 ACQUISITION AND OWNERSHIP COST DATA STUDIES</u>

Where data is not available on completed contracts, but the data is sorely needed for decisions on optimal MTBF and MTTR on future contracts, award study contracts to collect the data. Several of these have been concluded by BuShips and BuWeps. Another alternative is to require a new design contractor to do this first, as a basis for his design.

7.5 OWNERSHIP COST DATA PROGRAMS

Establish such activities as the Navy Maintenance and Materiel Management Project Group (36) and the BuShips Maintenance Management Project Office (37) to obtain the cost data needed for MTBF and MTTR decisions. Vigorously pursue full documentation of reliability, cost, and maintenance data during the life of the equipment, and make it available to the manufacturer for his analysis and action (27 p.217 item 4).

7.6 REFERENCE MANUALS

Contract for the development of a very concise reference manual containing not theory and analysis but the significant fact figures, and quantitative "rules of thumb" for direct use by contractor design engineers. An example of a "rule of thumb" is "Doubling the MTBF adds about 20% to Acquisition Cost".

7.7 TRADEOFF TOOLS

Contract for the development of new and more refined tradeoff tools relating design alternatives to cost. Simple research will go far toward refinement of the above 20% with variations for equipment categories, as well as toward realization of similar tools for ownership cost vs. MTBF and MTTR (27 p.214 item 6; p.216 item 13; p.219 item 3; 38 p.7).

7.8 CONTRACT TECHNIQUES

Develop realistic incentive contract techniques that encourage contractor expenditure up to that which achieves the optimal MTBF and MTTR, considering total cost.

Consider what happens on a straight cost-incentive contract that pays say 10% of Acquisition cost savings. If the contract target is state-of-the-art reliability and maintainability, it is to the contractor's advantage to spend as little as possible on reliability improvement as long as he thinks he knows how to design state-of-the-art goods. But he knows that he will be penalized for any extra expenditure to achieve better reliability or maintainability. The same is true of "value engineering" (39) clauses, which do not yet take into account ultimate customer savings.

Consider what happens on a reliability-incentive contract that pays say 0.3% added fee for each % operational reliability improvement in addition to the above cost-incentive. The cost of achieving 2% higher reliability is much greater at, say, 90% than it is at 70%. Therefore the more reliability a contractor achieves the less he is paid for it. There is always a reliability level beyond which the contractor is actually penalized for reliability improvement (38 p.9; 27 p.217 it ` 5). For the above figures (10) it is around 90% reliability.

Perhaps you will say "if this is the situation for a certain system, then the user should specify exactly what MTBF he requires." Indeed he should, but usually cannot. He cannot because today he does not know the cost to achieve various levels of reliability and maintainability. The Bureau will usually have to obtain these costs from contractors in order to locate the crest of the cost-effectiveness curve. This should occur roughly for the PIA, and later more precisely in competitive dialogue with contractors. Such costs will vary widely between contractors.

Another much-discussed solution is to give the contractors pertinent maintenance and logistic parameters in several study contracts, and let them submit cost-effectiveness analyses based on their own costs. With such analyses the Bureau should be able to locate the crest, and incidentally find out who knows what it costs to achieve, not just "control", reliability and maintainability.

Still another may be to simply award contracts on the basis of promised cost-effectiveness instead of cost, with incentives and penalties surrounding the promised value. This would oblige contractors to develop and use the kind of cost-effectiveness analysis tools outlined herein: and also to operate a continuous cost-effectiveness model incorporating Reliability and Maintainability prediction. Unlike reliability models, these would predict loss or gain of fee, guaranteed to get action in proportion to the real ultimate impact on the user.

As discussed (40) in detail by Dr. Hitch, DOD Comptroller, the problem of properly responsive incentives is very complex. Like yachting handicaps, incentive contracts invite design to the payoff formula. The problem is to make the formula exactly match the real BuShips objective, which is not usually as simple as the ratio of effectiveness to cost. But it does seem as though the potential payoff to the Bureau and taxpayers is worth considerable effort on one or more solutions to the problem.

7.9 MANAGEMENT VISIBILITY

Develop a realistic monthly reporting system, for BuShips and contractor management alike, that tells on one page whether the anticipated operational cost-effectiveness is going up or down. One example is shown in Figure 26.46. If a costly change was made to obtain higher MTBF, but the expected maintenance saving more than offsets it, then the report can show the trend line going to higher Cost-Effectiveness. Or if a test shows lower-than-planned MTBF, the trend depression shows how much can be afforded to correct it (38 p.11; 41 p.127).

7.10 DATA COLLECTION STUDY

Augment the current study to develop more effective and efficient failure reporting, data feedback, and corrective action procedures (see Chapter 9 and references 27 p.219, 42 p.356, and 28 p.4) to include failure cost reporting by the Bureau. By calculating indices at regular intervals, coding, and storing for easy retrieval, the time and cost of many other studies should be drastically reduced. Enough data should be collected to determine which components need further development, based on Total Cost (27 p.216 item 9)

7.11 SURVEYS

For critical systems, establish separate personnel, trained in the criteria for and applications of the data, to obtain Ownership Cost, manpower, MTBF and MTTR data. Experience has shown beyond all doubt that recording by the using and maintenance personnel is not reliable (44 p.29).

7.12 NAVY MACHINERY HISTORY CARD

When properly filled in, this provides very useful data. But often the very important hours of operation are not given (27 p.214 item 5; p.217 item 9). One report (44 p.65) states that the Navy failure reporting program is exceptional in concept, but has not been getting failures reported. At present only 10 to 20% reporting is achieved (27 p.217 item 10; 43 p.4 item 5). The date the equipment was put into operation should be entered, as well as the exact observation that led to maintenance action (27 p.217 item 9). While this card is not transmitted to the Bureau, it could provide excellent data for analysis of specific components.

7.13 MAINTENANCE SCHEDULES

The preventive and corrective maintenance schedules furnished by the contractor should be analytically worked out and based upon the failure rate curve and all costs involved (27 p.215 item 6,7).

MONTHLY COST-EFFECTIVENESS REPORT

SYSTEM and CONTRACTOR	COST-EFFECTIVENESS	EFFECTIVENESS					TOTAL COST in $millions			
		Perfor Capab.	Avail-abili.	Deliv. Effec.	Utili-zation	NET (PADU)	Acquisition Basic	Acquisition R&M	Owner-ship	TOTAL (sum)
	E/C	P%	A%	D%	U%	E%	C_a	C_r	C_o	C
POLAR K by "A"										
Required (est.)	(.95)	100	70	100	(95)	(66)	(20)	(2)	(48)	(70)
Predicted Now	1.31	100*	80*	95	95	72	20	3.0*	32	55
Last report	1.02	105	75	95	95	71	20	1.3	48	69
Actual Recent	.56	95	60	100	90	51	18	1.7	72	92
Cumulative	.22	90	50	90	70	28	18	0.3	108	126
POLAR K by "B"										
Required										
Predicted Now	1.78	95	90	90	95	73	19	6	16	41
Last report										
Actual Recent										
Cumulative										

*Design change authorized to obtain higher cost-effectiveness via reliability, at increased Acquisition Cost and some sacrifice of performance.

8. SUMMARY

In this lecture we have shown that the cost consequences of inadequate reliability and maintainability are very substantial. They constitute a major drain on the defense dollar resources, which dollars might be better spent on other procurement.

Every decision between design alternatives should be evaluated on the basis of consequent system Effectiveness in relation to consequent Total Cost of Acqusition and Ownership. Delivery effects are included in Effectiveness and Costs. This is virtually the only sound basis upon which Reliability and Maintainability requirements can be established, and concurrently justified.

Comparative analysis between alternatives requires data only on things that change between alternatives, thus works well with limited data. Absolute prediction of Cost-Effectiveness requires much more data.

Reliability and Maintainability Acquisition Cost data must be obtained from contractors as part of proposals and refined during design and production. Ownership Cost data must be obtained from fleet operations and shipyards.

Contracts can be written so as to provide cost-effectiveness data, and eventually should be written in such a way that the contractors fee is directly related to achieved cost-effectiveness.

As Rear Admiral Emerson Fawkes, USN, said, "The use of the cost-effectiveness ratio in making technical, management, and military decisions is the way of life."

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CHAPTER 27

DEFINITIONS

Chapter 27

DEFINITIONS

Until the reader or listener sees rigorous technical definitions for common words used in a technical sense, he takes them to have the "common usage" meaning. But since very few readers actually see standardized technical definitions, adequate communication demands that technical definitions be consistent with, and fall within, the dictionary and common usage meanings. To do otherwise leads the average reader astray, cutting off the very understanding that is sought.

This problem commonly occurs in new technologies, such as reliability and maintainability. MIL STD 721A and MIL STD 778 have been issued in an attempt to standardize terms commonly used in these technologies. But new technologies are dynamic, and the definitions that worked yesterday are often found inadequate tomorrow. Thus many of the 721A and 778 definitions need improvement for communciation with design engineers in todays technology.

In this chapter, therefore, we list selected definitions of words as used in this text. Wherever a 721A or 778 definition is adequate, we use it. Where it is not, we provide a workable definition followed by an indented quotation of 721A or 778 and an explanation of its limitations.

Also some additional terms actually needed and used in the advancing technology are defined. The following definitions are grouped according to their relationship to each other, rather than alphabetically.

1. RELIABILITY DEFINITIONS

1.1 FAILURE is the inability of the system or component to perform the required function. As defined in 6.2 and 6.10 below, "system" and "component" are used in a broad sense, and specifically include human components.

> MIL STD 721A says "Failure is the inability of materiel to perform its required function within previously-established limits." "Materiel" means "hardware" at all levels, specifically excluding human components whose failure must be included. "Previously established limits" may apply to testing but not necessarily to the actual operational limits.

1.2 OPERATING TIME is the time during which the system or component is performing its intended function.

MIL STD 721A is identical except materiel is used in place of system or component, but again there must be no exclusion of human components.

Operating time is quite significant for many purposes, but often cannot be related directly to failures. To obtain failure rate or MTBF it is necessary to use Stress Time, defined below.

1.3 STRESS TIME is the time during which stresses occur that can induce failure. It includes Operating Time. Such stresses commonly occur during standby and maintenance.

1.4 MISSION TIME (t) is the period of time in which an item must perform a specified mission. (MIL STD 778).

In the above, "item" includes systems and components. "Specified mission" normally means the specific task whose completion without failure is required.

1.5 MEAN TIME BETWEEN FAILURES (MTBF) (T) is the average Stress Time between Failures. (See Stress Time).

MIL STD 721A says "MTBF is, for a particular interval, the total measured functioning time (or cycles, miles, events, etc.) of a population of materiel divided by the total number of failures within the population during the measured period". Again it cannot be limited to "materiel" and the time may be more than "functioning" time. MTBF is the primary index of design reliability, commonly expressed in hours. It is the reciprocal of Failure Rate.

1.6 MEAN CYCLES BETWEEN FAILURES (MCBF) is the average number of stress cycles between failures. An operational Stress Time/cycles relationship may be used to convert to equivalent MTBF for analysis.

1.7 FAILURE RATE (λ), at any point in the life of the system or component, is the incremental change in the number of failures per associated incremental change in the measure of life (time, cycles, miles, events, etc., as applicable)." When failure rate is assumed constant, it is the average number of failures per unit Stress Time. It is commonly expressed in failures per million hours, and is the reciprocal of Mean Time Between Failures.

MIL STD 721A is identical to the primary statement above, except that "materiel" excludes human components.

1.8 WEAROUT FAILURE is one that occurs as a result of deterioration processes or mechanical wear and whose probability of occurrence increases with time (MIL STD 721A).

1.9 RELIABILITY (R) is the probability that the system or component will perform its intended function for a specified period under stated conditions.

MIL STD 721A is identical except that "materiel" excludes human components. The word is also commonly used to express the fraction of systems or components that operate without failure for the Mission Time duration.

1.10 CONFIDENCE LEVEL is the probability that a given statement is correct, or the chance that the true value lies between two confidence limits (the confidence interval) (MIL STD 721A).

The commonest use of the term is the probability that the true value of reliability is at least equal to a specified lower limit.

2. MAINTAINABILITY DEFINITIONS

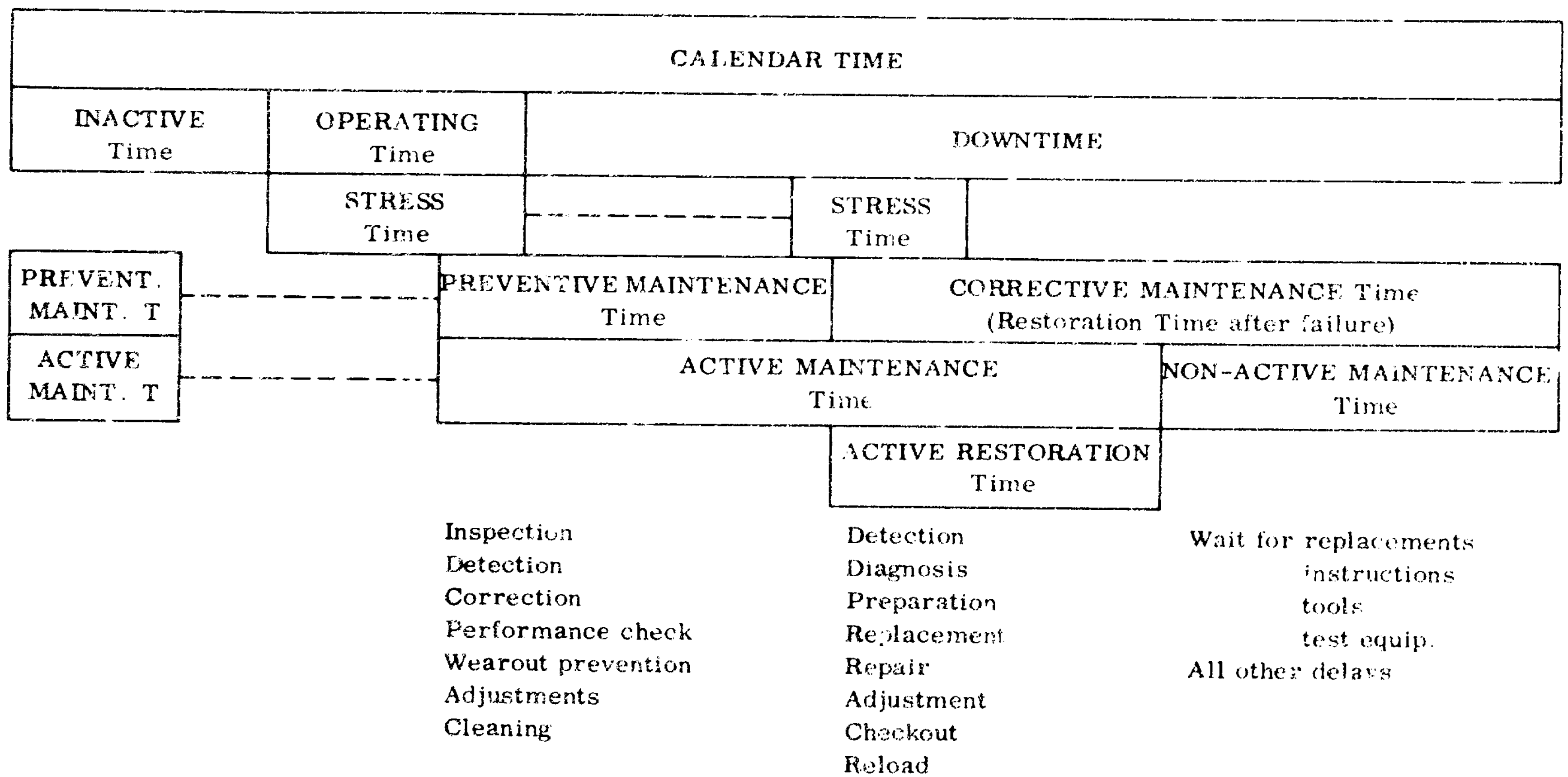
Figure 27-6 will be found helpful in understanding the Maintainability and Availability definitions.

2.1 DOWNTIME is that portion of calendar time during which the item is not in condition to perform its intended function (MIL STD 778).

"Item" refers to systems or components. Note that downtime is maintenance time, but excludes any during which the system or component continues to operate, as well as any that can be instantly interrupted.

2.2 PREVENTIVE MAINTENANCE TIME is the maintenance time to retain an item in satisfactory operational condition by providing systematic inspection, detection, and prevention of incipient failure. It is made up of performance measurement, care of mechanical wearout items, front panel adjustment, calibration and alignment, cleaning, etc. (MIL STD 778).

AVAILABILITY TIME CHART



THIS CHART SHOWS RELATIONSHIPS OF TERMS AS USED IN THIS HANDBOOK

2.3 CORRECTIVE MAINTENANCE TIME is the time that begins with the observance of a malfunction of an item and ends when the item is restored to a satisfactory operating condition. It may be subdivided into Active Maintenance Time and Non-Active Maintenance Time (MIL STD 778).

This is also called "Repair Time" by the Navy and "downtime" or "unscheduled maintenance time" by many industries. To avoid confusion in this text we have tried to avoid use of these alternative words for this meaning.

2.4 ACTIVE MAINTENANCE TIME is the time during which preventive and corrective maintenance work is actually being done on the item. (MIL STD 778)

2.5 NON-ACTIVE MAINTENANCE TIME is the time during which no maintenance is being accomplished on the item because of either supply or administrative reasons (MIL STD 778)

"Supply or administrative reasons" means waiting for any item, or any other reason.

2.6 ACTIVE RESTORATION TIME is the Corrective Maintenance Time during which work is actually being done. It includes detection, diagnosis, preparation, replacement or repair, adjustment, checkout, and reload time to the extent each is necessary.

MIL STD 778 says "active REPAIR time is the time during which one or more technicians are working on the item to effect a repair." It is felt that to design engineers the word "repair" implies only one of many steps in the restoration after a failure.

2.7 MEAN TIME TO RESTORE (MTTR) is the statistical mean of the distribution of times-to-restore. It is the summation of active restoration times during a given period of time divided by the total number of failures during the same time interval.

MIL STD 778 is identical except for the word "repair" instead of "restoration", which implies only a portion of the task. MTTR is the mean time for restoration to full performance capability, including detection, diagnosis, preparation, replacement or repair, adjustment, checkout, and (for loss of content) reload, and any waiting for replacements, instructions, test equipment, etc.

2.8 MAINTAINABILITY is the speed or economy with which a system or component can be kept in, and/or restored to, full performance capability. A principally-used measure is the average number of failures restored per hour of Corrective Maintenance time, which is the reciprocal of MTTR. Another is the fraction of attempts wherein restoration is completed in a specified time, or the probability that it will be completed in that time. Another is the functional time obtained per dollar cost of preventive and corrective maintenance.

MIL STD 778 says "maintainability is a characteristic of design and installation which is expressed as the probability that an item will conform to specified conditions within a given period of time when maintenance action is performed in accordance with prescribed procedures and resources." Unfortunately this wording seems to include predicted reliability and availability within maintainability and the words "probability", "will", "specified", "given", and "prescribed" preclude use of the word "maintainability" to express what actually happens in operation.

3. AVAILABILITY DEFINITIONS

3.1 AVAILABILITY (A) is the fraction of the total desired operating time that the system or component is operable.

MIL STD 721A is identical to the above, except that the word "materiel" excludes human components. MIL STD 778 defines the same thing as "availability (operational) is the probability that a system or equipment when used under stated conditions and in an actual supply environment shall operate satisfactorily at any given time."

3.2 DEMAND AVAILABILITY (A_d) is the fraction of required Stress Time that the system or component can perform its function upon demand. It may be expressed as MTBF/(MTBF + MTTR) when there is no stress during maintenance, but as 1 - MTTR/MTBF when there is stress during maintenance. It is the Availability assuming that Preventive Maintenance can be interrupted or will be done in Inactive Time.

3.3 CONTINUOUS AVAILABILITY (A_c) is the fraction of long-term Stress Time that the system or component can perform its function, with preventive maintenance accomplished. One expression for it is 1 - MTTR/MTBF - T_p/MTBF where T_p is the preventive maintenance time ratio to number of failures.

3.4 OPERATIONAL READINESS is the fraction of total number of systems or components that are in condition to perform their function. It is usually equal to Continuous Availability.

4. EFFECTIVENESS DEFINITIONS

Figure 27-11 may help to visualize the relationships between effectiveness factors, cost elements, and cost-effectiveness.

4.1 EFFECTIVENESS (E) is a quantitative index expressing accomplishment or worth of an operational system or component. It is a function of performance capability, delivery effectiveness, availability and/or reliability, and utilization. It may be the simple product of these factors.

> MIL STD 721A says "effectiveness is the probability that the materiel will operate successfully when required." Unfortunately this definition is not distinguishable from reliability, and does not sufficiently identify the constituents.

4.2 SYSTEM EFFECTIVENESS is the Effectiveness of a system.

4.3 PERFORMANCE CAPABILITY (P) is a quantitative figure of merit expressing the system or component capability of performing desired functions, assuming no delivery delay, no failures, and full utilization.

4.4 DELIVERY EFFECTIVENESS (D) is the ratio of system or component effectiveness as degraded by late delivery, to the effectiveness had it been available when needed. It is also sometimes called Schedule Effectiveness or Schedule Adherence.

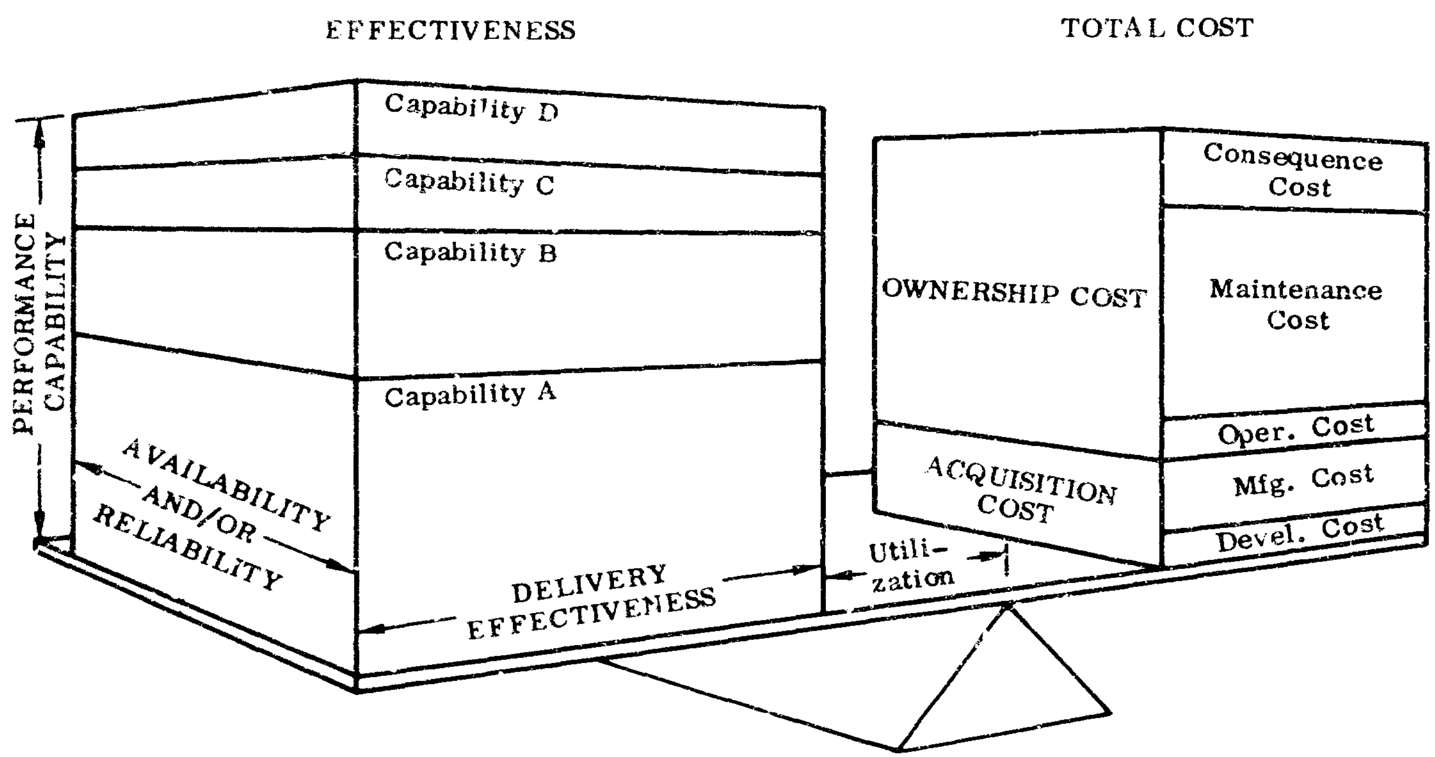
4.5 UTILIZATION (U) is the fraction of performance capability actually utilized due to the specific application and environment encountered. It includes all effectiveness degradation due to causes external to the system or component itself.

4.6 USEFUL LIFE (L) is the system or component life, in years, as limited by obsolescence, utility, and wearout.

5. COST DEFINITIONS

5.1 DEVELOPMENT COST (C_d) is the total cost of operations analysis (during conceptual phase), design (during conceptual and definition phase), hardware design, hardware prototypes, test, evaluation, and schedule slippage for this phase.

THE ELEMENTS OF COST-EFFECTIVENESS



5.2 PRODUCTION COST (C_p) is the total cost for quantity procurement, manufacture, installation, tests, training, and schedule slippage for this phase.

5.3 OPERATION COST (C_o) is the total cost, for the system or component lifetime, of those personnel, facilities, utilities, consumables, and special inputs required for operation, excluding those for maintenance.

5.4 MAINTENANCE COST (C_m) is the total cost, for the system or component lifetime, of those personnel, facilities, spare components, logistics, and diagnostic aids required for maintenance.

5.5 CONSEQUENCE COST (C_c) is the total cost, for the system or component lifetime, generated external to the system or component as a consequence of its failures. These may include damage or loss of other systems or components, including human productivity.

5.6 ACQUISITION COST (C_a) is the total cost for Development (C_d) and Production (C_p) defined above.

5.7 OWNERSHIP COST (also called User Cost, C_u) is the total cost for Operation (C_o), Maintenance (C_m), and Consequence (C_c) defined above.

5.8 TOTAL COST (C_t) is the total cost for Acquisition (C_a) and Ownership (C_u) defined above.

5.9 COST-EFFECTIVENESS is the actual quantitative accomplishment or worth of an operational system or component, relative to its Total Cost, taking delivery time into account. It may be expressed as a ratio of Effectiveness (including delivery effectiveness) to Total Cost (including late delivery costs). Where Effectiveness can be expressed as Worth in dollars, Cost-Effectiveness can be very significantly expressed as Effectiveness minus Total Cost, or Net Gain or "profit".

6. GENERAL DEFINITIONS

6.1 ACCELERATED LIFE TEST is a test at excessive stress or environment to reduce test time, and implies adequate correlation to normal stress life.

6.2 COMPONENT is a constituent of a higher-level system or component. It usually means a functional hardware assembly at any level between Parts and Systems, but can include human components of systems.

6.3 CRITICAL COMPONENTS are those whose reliability and application are such that they require special attention to preserve system reliability. The criterion for such designation may be a Criticality (defined below) above a specified level.

An older criterion is that they are used in such a way that their failure would cause system failure, which criterion does not take the component reliability into account.

6.4 CRITICALITY of a component is its quantitative contribution, relative to all other components, to predicted system failure rate. A CRITICALITY RANKING is a list of components in the order of their decreasing probability of causing system failure. Thus criticality depends upon both component failure rate and the way it is used.

6.5 LIFE TEST is any test at simulated normal operating stress and environment from which failure vs. stress time data is derived. Examples are sequential life tests, "Agree" tests, MTBF tests, etc.

6.6 OVERSTRESS TEST is any test in which stress and/or environment is made progressively more severe until either failure occurs or adequate safety margin is demonstrated.

6.7 PART is the lowest-level component of an assembly, not usually subject to further disassembly.

6.8 REDUNDANCY is the existence of more than one means for accomplishing a given function (MIL STD 721A).

6.9 STRENGTH/STRESS ANALYSIS is the comparison of strength distribution with anticipated stress distribution, to determine safety margin or the probability of no failure of a "population".

6.10 SYSTEM is used primarily to mean the overall man-machine complex to accomplish the desired functions. But it also is used to mean a group of components that work together to accomplish the functions. Examples are weapon system, propulsion system, or hydraulic system.

6.11 VALUE ENGINEERING is the determination of alternative means of accomplishing required component functions at lower cost, without degradation of performance capability, reliability or maintainability.

6.12 VERIFICATION (of R & M) is the estimation of achieved reliability or maintainability by accumulation of factory test, life test, overstress test, or operational data. Analytical prediction and stress margin analysis do not actually verify, but may provide the only achievable assurance in many cases.

* U. S. GOVERNMENT PRINTING OFFICE 1965 O - 790 - 118