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DISCRETE RELIABILITY GROWTH

by

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Thesis Advisor: W. M. Woods

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Discrete Reliability Growth

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ABSTRACT

Three methods for weighting an exponential regression model to estimate discrete reliability growth were derived and tested. The first method systematically applies greater weight to test phases whose estimates have less variability. The second method similarly applies heavier weight to the most recent test phase estimate. The third method allows the user to choose the weighting scheme.

These methods were evaluated against eight patterns of actual reliability by altering a previously developed Monte-Carlo simulation. Their performance was then compared to the unweighted exponential regression and Maximum Likelihood Estimate With Discounting (MLEWD) models. The second weighting method appears to perform the best under rather general constraints. Also, comparison is made of the least squares estimates for reliability growth using two different unbiased estimates for the negative of the natural logarithm of the failure rate.

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I. INTRODUCTION

Systems and equipment often go through several phases of development during which the reliability is assessed and the components or design are appropriately modified. From these early assessments, project managers need to make predictions regarding the ability of the system or equipment to meet reliability specifications by the contracted acceptance or delivery date. Some conventional estimators of reliability disregard data related to immature systems and use only that data obtained from the final product in verifying reliability. This practice is extremely inefficient, costly and occasionally, infeasible. Using all available test data would not only permit a manager to monitor the development process more successfully but at a substantial savings to all parties involved.

Reliability growth models are useful in estimating the reliability of both immature and mature systems. Continuous and discrete versions of models exist. Models which employ attribute test data are discrete while those based on time to failure data are continuous. Only discrete models will be addressed in this thesis. Both of these versions make use of all available test data and are often used in conjunction with a technique known as failure discounting. This is a process whereby an increasing fraction of a failure is repeatedly diminished as greater amounts of subsequent data is accumulated without repeat of the same failure.

Models evaluating data which have been adjusted using a failure discounting scheme have performed well in estimating actual reliability [Ref. 1:pp. 52-55]. Relying on discounting techniques has its drawbacks however. In order to employ the straight percent discounting method, for example, the user must select two parameters, N and F. F is the fraction each failure will be discounted and N is the number of successive successes which must be achieved prior to applying the discounting method. No rules have been developed as to <u>how</u> these parameters should be selected and no guidance other than to "use good engineering judgment" [Ref. 1:p. 50] has been offered on the subject.

The objective of this paper is to provide the user of a reliability growth model with an alternative to failure discounting which will produce comparable results. To this end, the Monte-Carlo simulation developed by Captain James Drake and modified by Captain James Chandler was altered to include a weighted exponential regression model. This model can use one of three methods of weighting.

Method one is based on the idea that the variances of the observables are not all equal and hence some are more reliable than others. To accommodate this fact, weights in this method are "heavier" for observables with lower variances. Method two systematically gives more weight to the most recent test phase motivated by the idea that the most recent version of the system is likely to be the most reliable. Method three is an extension of this idea. In this method, the user is permitted to subjectively select how much weight he desires to give each phase. This might produce successful results if the user has an intimate knowledge of the development process. He could then possibly choose to give little weight, say, to a phase he knew was conducted poorly or contained problems that he was certain were since corrected. Each of these methods was evaluated and compared to previously developed models using eight different actual reliability growth patterns. These comparisons are contained in Chapter VI.

As a further modification to previous work which primarily explored the "test-fix-test" methodology, i.e. only one failure per phase of testing permitted, this thesis investigates the effect of using an alternative unbiased estimator of the exponential regression parameter of a "test-find-test" scenario.

The following chapter will address previous work in the area of reliability growth models. The motivation for altering the exponential regression parameter is discussed in Chapter III and the weighted Regression Model and the derivation of the three methods of weighting are developed in Chapter IV. A brief description of the models with which the weighted model will be compared is presented in Chapter V. The comparisons under varying patterns of actual growth is treated in Chapter VI. A summary, conclusions and recommendations for further study are discussed in Chapter VII.

II. PREVIOUS WORK

A. BACKGROUND

This thesis is the third in a recent sequence on the subject of reliability growth. The initial work was completed by Captain James Drake [Ref. 1]. In his study, Captain Drake developed a Fortran program to evaluate the performance of three reliability growth models; namely, the maximum likelihood estimate model, the exponential regression model, and the weighted average model. These models were evaluated in conjunction with two failure discounting methods, the confidence limit (C.L.) method and the straight percent discounting method. The C.L. method is referred to as the Lloyd discounting method in Drake's thesis. In addition, Captain Drake varied the parameters of each of the discounting methods to evaluate their effect on the performance of these models. The "actual" or known reliability growth pattern against which these models were compared was generated by Monte-Carlo simulation. In this simulation, the user inputs the reliability during the first phase of testing of each component which may possibly fail (i.e., of each potential failure cause). The program then generates an "actual" growth pattern from these values for the remaining phases of testing. The user of this program relinquishes strict control of the actual reliability growth pattern beyond the first phase and, although manipulation of another parameter (specifically, "FRIMP") can produce the pattern in a general desired form, the simulation is incapable of producing a decreasing pattern.

Captain James Chandler modified Captain Drake's program to permit the user complete control of the actual reliability growth pattern at each phase of development. In his version of the program, the user is required to input the reliability of each potential failure cause at each phase. Additionally, if more than one failure is permitted per phase of testing, the value must be replicated for each failure in that phase [Ref. 2]. To reduce the amount of required user input, this process was modified in this thesis so that the amount of information required per phase is the same regardless of the number of failures per phase permitted. The required information is contained in the User's Guide, Appendix A to this thesis.

Captain Chandler also altered the C.L. failure discounting method to allow the user control of the discount interval. This was motivated by the results of the original thesis which indicated that employment of the C.L. method resulted in overly optimistic estimates regardless of the model used or the actual reliability pattern generated. This was attributed to the fact that the original C.L. method diminishes the weight of a failure after each following success.

B. RESULTS OF PREVIOUS WORK

The weighted average reliability growth model was eliminated as a potential model in the early stages of the original analysis. This was due to its consistent overestimation of actual reliability which was only amplified by employment of either of the failure discounting methods. This model was discarded in subsequent work as well.

The remaining two models accurately tracked a wide range of reliability growth patterns. The Maximum Likelihood Estimate with Discounting model, (MLEWD), generally "tended to underestimate actual reliability in early phases and slowly converge to the actual value with increased test data" [Ref. 1:p. 48]. This model also exhibited smallest variance of all models evaluated. The negative aspect of the MLEWD model is that the choice of discounting parameters is critical to successful implementation and guidance in their selection is non-existent. The potentially drastic effects of different parameter choices is discussed in Chapter V.

The exponential regression model also performed well against various actual reliability growth patterns and was far less sensitive to the choice of discounting parameters than the MLEWD model. The difficulty with this model is that it is highly variable in the early phases of testing although it generally stabilized after four phases. This was considered acceptable since most development processes allow for more extensive testing.

The C.L. discounting method was not recommended for employment with either model as its use only occasionally produced results comparable to the straight percent discounting method without possessing its corresponding flexibility.

Captain Chandler evaluated these two models along with the standard single phase maximum likelihood estimate against eight reliability patterns. His results indicated that both the MLEWD and the exponential regression model were superior in all respects to the standard estimate. Additionally he found that the modification made to the C.L. discounting method resulted in instances of superior performance to the original C.L. method (although not to the straight percent discounting method). The remainder of his work substantiated the conclusions drawn by Captain Drake and included additional observations regarding the case of declining reliability.

Both authors conducted all simulations for the test-fix-test scenario.

III. MOTIVATION FOR IMPLEMENTING Y_k^*

The exponential regression reliability growth model was developed by H. Chernoff and W. M. Woods. Its derivation is fully detailed in Ref. 3 and Chapter IV. In this model the reliability after the k^{th} change is modeled by $R_k=1-e^{-(\alpha+\beta k)}$. For the purposes of this chapter it is sufficient to understand that the model estimates the reliability in Phase k as:

$$\hat{R}_k = 1 - e^{-(\hat{\alpha}_k + \hat{B}_k k)} * \tag{3.1}$$

where $\hat{R}_k$ is the reliability estimate, and the estimates $\hat{\alpha}_k$ and $\hat{\beta}_k$ for α and β at the conclusion of testing in the k^{th} phase are obtained using linear regression methods and an unbiased estimator for $(\alpha_k + \beta_k k)$.

The unbiased estimator is:

$$Y_{jk} = \begin{cases} 1 + 1/2 + 1/3 + \dots 1/(X_{jk} - 1) & for \;\; X_{jk} \geq 2 \\ 0 & otherwise \end{cases} \tag{3.2}$$

where X_{jk} is the number of trials between the $(j-1)^{st}$ failure and the j^{th} failure (including the j^{th} failure) in the k^{th} phase.

---

* The symbol B and ß denote the same constant throughout this thesis. B is used for ß within equations.

Let F_k = the number of failures in the k^{th} phase. Since $X_{1,k}, X_{2,k}, \ldots X_{F_k,k}$, are independent random variables then

$$\overline{Y}_k = (Y_{1k} + Y_{2k} + \ldots Y_{F_k k})/F_k \tag{3.3}$$

is also unbiased.

Previous work incorporates this estimator of $(\alpha + \beta_k k)$ however an unbiased estimator which has minimum variance of all estimators has since been developed by W. M. Woods; this estimator is as follows:

$$Y_k^* = 1/F_k + 1/(F_k + 1) + \ldots 1/(X_{F_k} - 1) \tag{3.4}$$

Replacing $\overline{Y}_k$ with Y_k^* in the exponential regression model provides a more accurate estimate of reliability.

Table 1 is the result of performing ten thousand replications of one phase negative binomial (Pascal) test data with actual reliability R and comparing the model to this value of R employing $\overline{Y}_k$ and again using Y_k^*. This table demonstrates that while reliability predictions using Y_k^* and $\overline{Y}_k$ are both conservative, those using Y_k^* more closely estimate actual reliability, have smaller variances and a smaller mean square error.

The parameters used in this simulation are as follows:

F_k = The number of failures in phase k was fixed at 3 for all cases

X_{F_k} = The number of trials to the F_k failure.

N = The number of replications = 10,000

k = The number of phases = 1

$\bar{Y}_1$ and Y_1^* are as in equations 3.3 and 3.4 respectively.

TABLE 1. COMPARISON OF Y_k^* VERSUS $\bar{Y}_k$ AS THE ESTIMATOR OF A_k

Actual Reliability	$\bar{\hat{R}}_1$	$\bar{\hat{R}}_1^*$	$s_{\hat{R}}^2$	$s_{\hat{R}^*}^2$	$\frac{1}{N}\sum_{i=1}^{N}(\hat{R}_i - R)^2$	$\frac{1}{N}\sum_{i=1}^{N}(\hat{R}_i^* - R)^2$
.5	.450058	.452505	.053019	.051689	.053714	.053798
.6	.548045	.551360	.049514	.047326	.051683	.049269
.8	.757407	.762589	.026653	.024093	.029267	.024800
.9	.872237	.876579	.011429	.009899	.012034	.009456
.95	.933223	.936339	.004889	.004163	.004280	.003227
.99	.985111	.986071	.001414	.001348	.002513	.001747

Though these results prove that Y_k^* is superior to $\bar{Y}_k$ as an estimator of the coefficient of the exponential term, the impact of this improvement is disappointingly trivial. Figures 1a - 1h depict the results of employing Y^* and $\bar{Y}$ to the exponential regression model for actual reliability patterns 1-8. As one can see from both the Table and the figures, the effect of this change takes place in the third decimal value. In practice, changes of this magnitude are hardly useful. Still, since Y_k^* is an improvement over $\bar{Y}_k$ it is retained as the method of estimating (a and ßk) throughout the remainder of this thesis.

Note: In all figures, A=actual; $*=Y^*$ and $- = \bar{Y}$

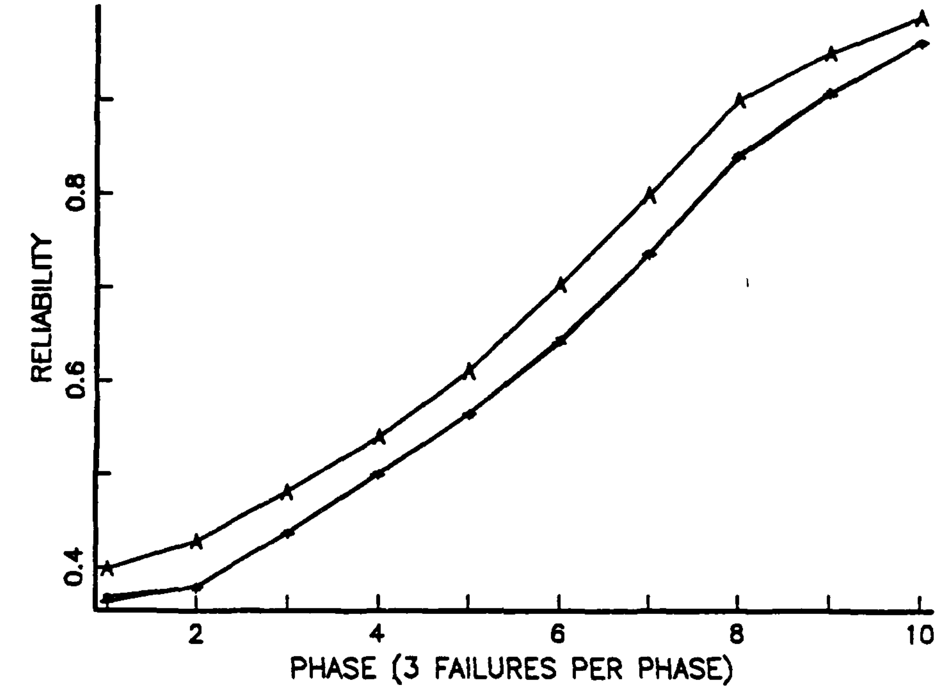

Figure 1A. Y* vs. $\bar{Y}$, Pattern 1

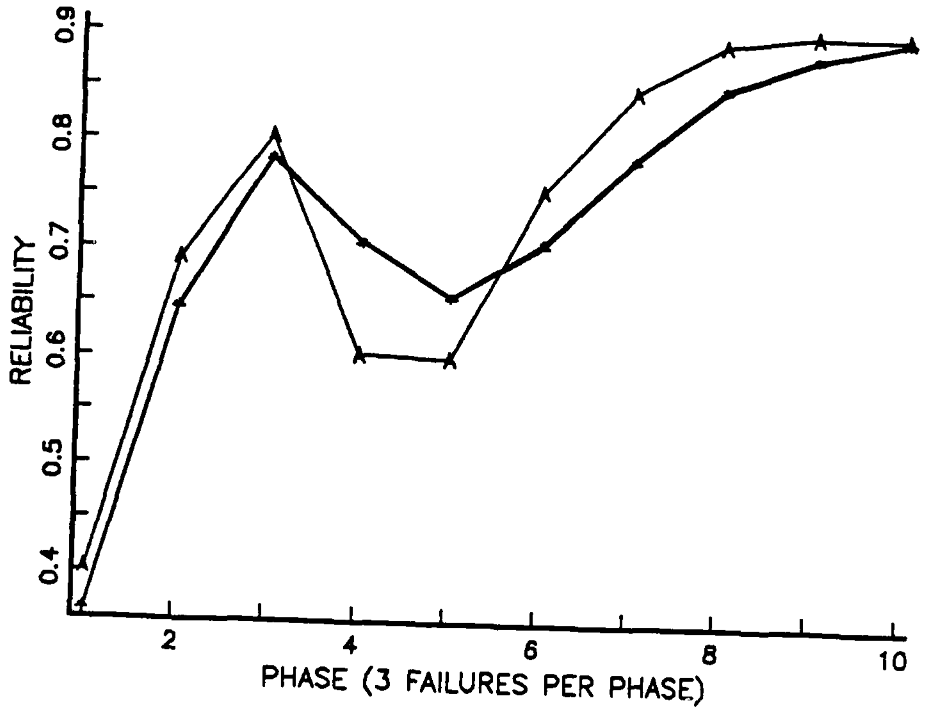

Figure 1B. Y* vs. $\bar{Y}$, Pattern 2

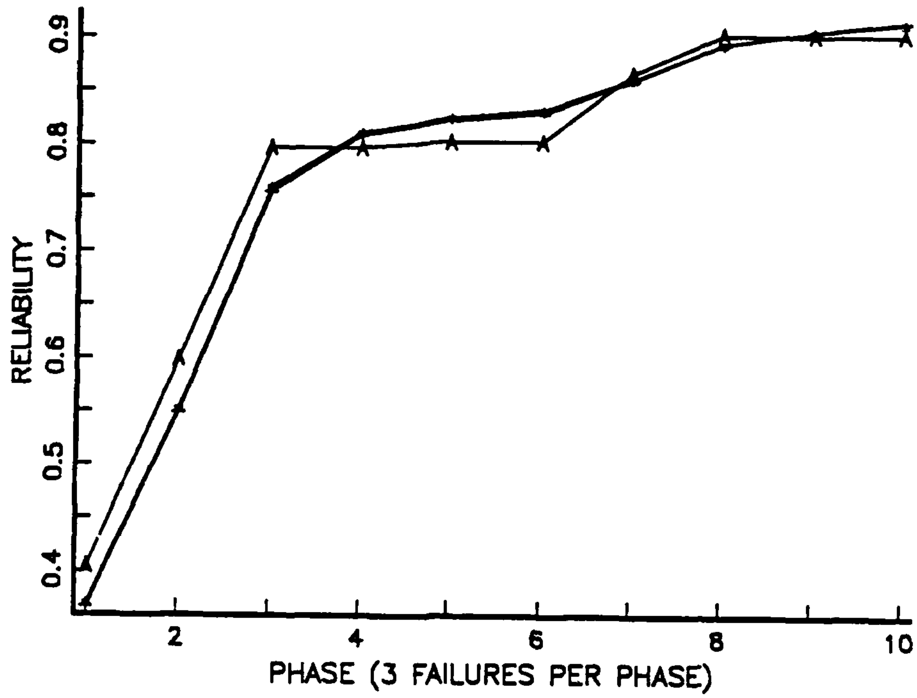

Figure 1C. Y* vs. $\bar{Y}$, Pattern 3

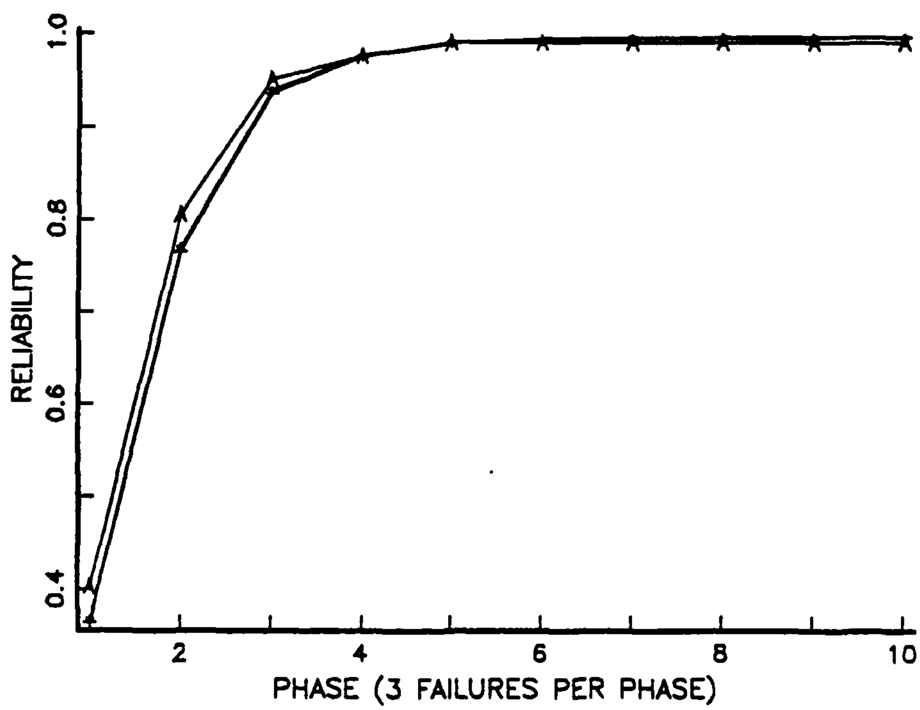

Figure 1D. Y* vs. $\bar{Y}$, Pattern 4

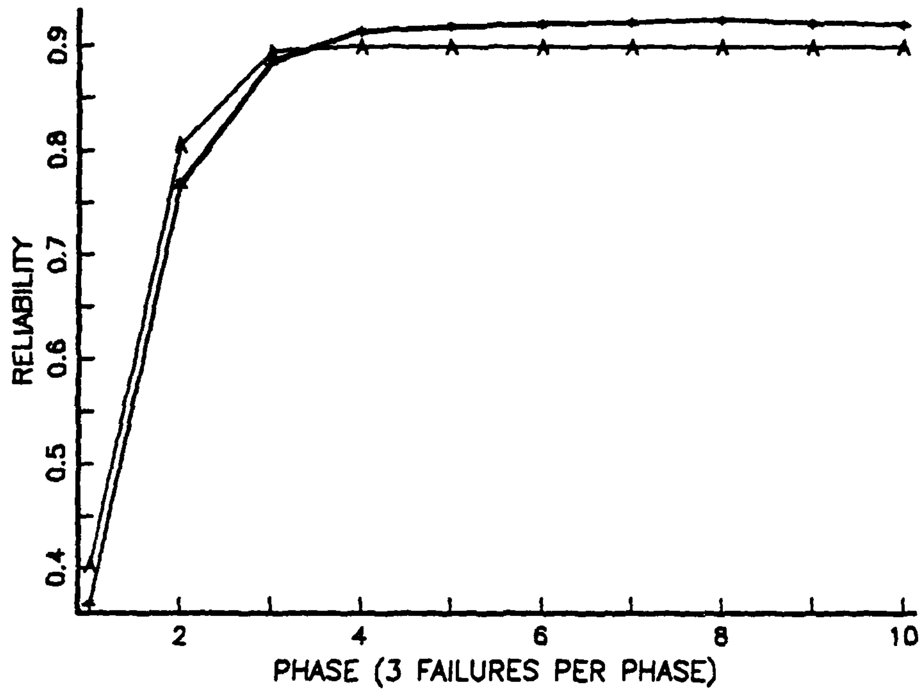

Figure 1E. Y* vs. $\bar{Y}$, Pattern 5

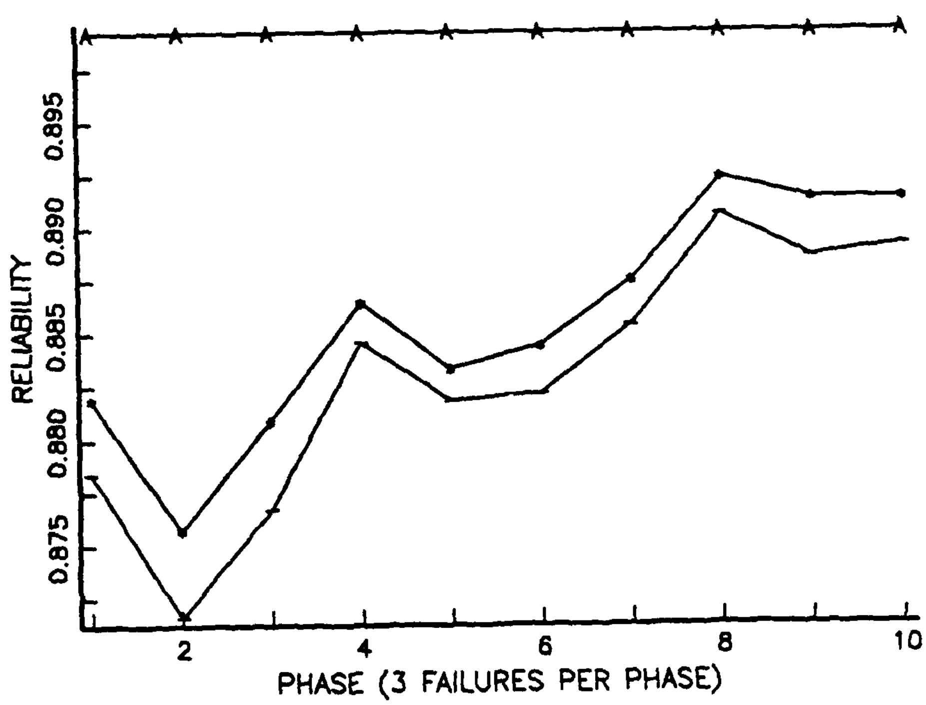

Figure 1F. Y* vs. $\bar{Y}$, Pattern 6

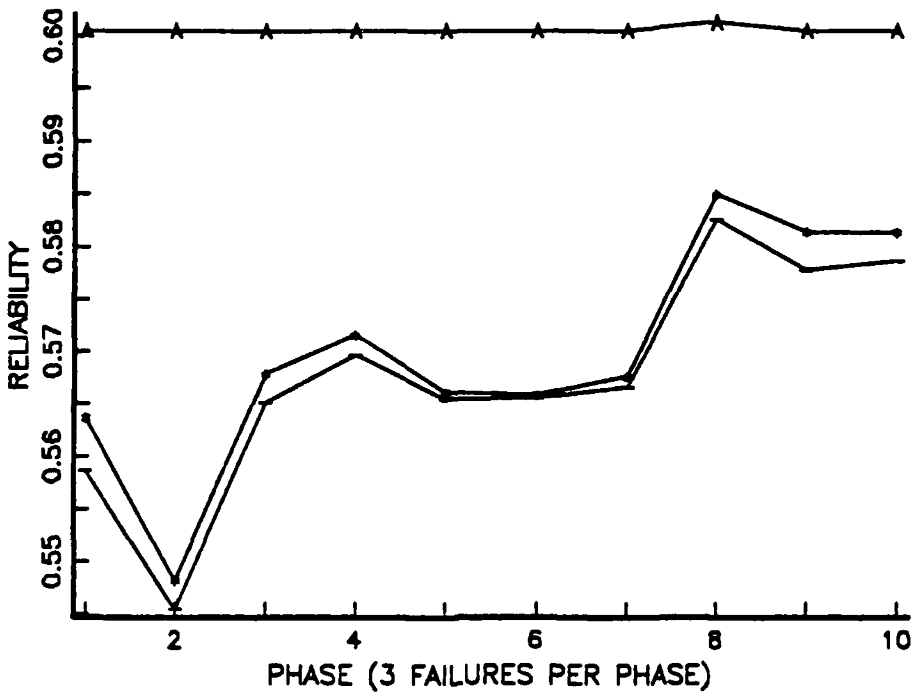

Figure 1G. Y* vs. $\overline{Y}$, Pattern 7

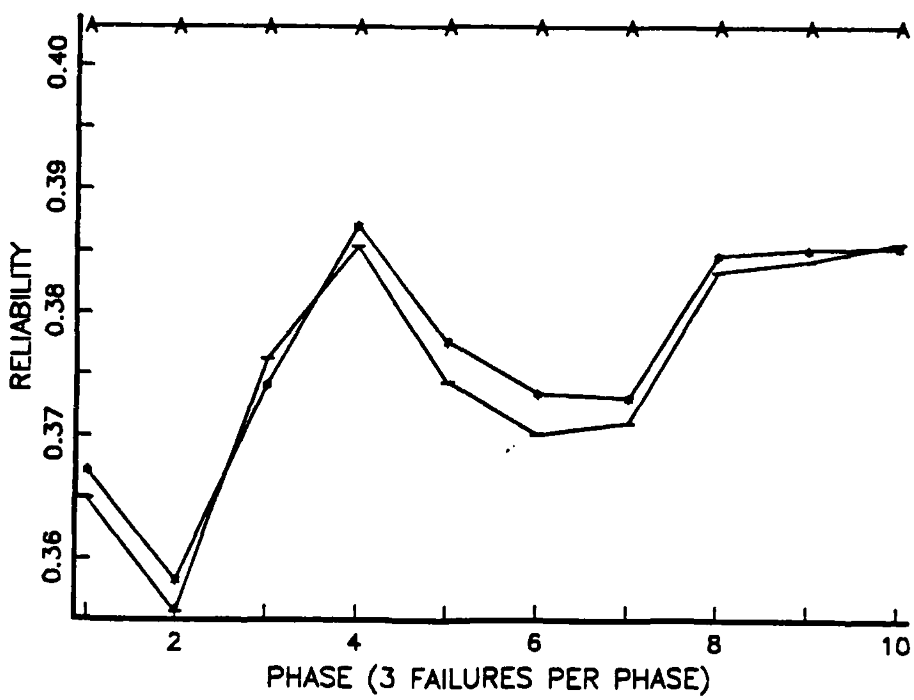

Figure 1H. Y* vs. $\overline{Y}$, Pattern 8

IV. THE WEIGHTED EXPONENTIAL REGRESSION MODEL

A. THE EXPONENTIAL REGRESSION MODEL

The exponential regression model obtains sequentially updated estimates $\hat{R}_k$ of the reliability R_k which denotes true reliability after the k^{th} phase. The basic model for R_k is:

$$R_k = 1 - e^{-(A_k)} \tag{4.1}$$

In the exponential regression model, linear regression is used to estimate $A_k = (\alpha + \beta k)$ by $\hat{A}_k$ where

$$\hat{A}_k = \hat{\alpha}_k + \hat{B}_k k \tag{4.2}$$

The exponential regression estimate of reliability is then:

$$\hat{R}_k = 1 - e^{-(\hat{\alpha}_k + \hat{B}_k k)} \qquad k = 1,2,\ldots \tag{4.3}$$

and $\hat{\alpha}_k + \hat{\beta}_k k$ is estimated sequentially at each phase. This results in a model which is capable of tracking changing reliability. In order to estimate the parameters α_k and β_k one must first calculate the unbiased estimator, Y_k^*. As discussed in Chapter III, Y_k^* is the unbiased estimator with minimum variance and has been implemented in this version of the model.

Let:

F_k = The number of failures in the k^{th} phase

X_{F_k} = The total number of trials to and including the F_k failure in the k^{th} phase.

Then:

$$Y_k^* = \begin{cases} 1/F_k + 1/(F_k+1) + 1/(F_k+2) + \dots 1/(X_{F_k}-1) & \text{for } X_{F_k} \geq F_k + 1 \\ 0 & \text{for } X_{F_k} = F_k \end{cases} \qquad (4.4)$$

As an example, if the testing in the fifth phase continues until three failures occur and the third failure occurs on the eighth trial then:

$$Y_5^* = 1/3 + 1/4 + 1/5 + 1/6 + 1/7 = 1.092857$$

The least squares estimates for β_k and α_k are :

$$\hat{B}_k = \frac{\sum_{i=1}^{k} [(i-\bar{k}) \times Y^*_k]}{\sum_{i=1}^{k} (i-\bar{k})^2} \qquad (4.5)$$

$$\hat{\alpha}_k = \bar{\bar{Y}}_k - \hat{B}_k \bar{k} \qquad (4.6)$$

where $\bar{k} = (1+2+3+\dots k)/k$

$$\bar{\bar{Y}}_k = (Y^*_1 + Y^*_2 + Y^*_3 + \dots Y^*_k)/k$$

Replacing the unknown parameters, α_k and β_k with their estimates $\hat{\alpha}_k$ and $\hat{\beta}_k$ in equation (4.3) yields:

$$\hat{R}_k = \begin{cases} 1 - e^{-(\hat{\alpha}_k + \hat{B}_k k)} & \text{for } k > 1 \\ 1 - e^{-Y^*_1} & \text{for } k = 1 \end{cases} \qquad (4.7)$$

B. THE WEIGHTED EXPONENTIAL REGRESSION MODEL

The weighted exponential regression model is identical to the unweighted exponential regression model above with the following exceptions:

Let:

w_i = the weight applied to the estimate in phase i.

Replace all occurrences of k in the calculation of the unweighted model with:

$$\bar{k}_w = \frac{\sum_{i=1}^{k}(w_i - i)}{\sum_{i=1}^{k} w_i} \tag{4.8}$$

and replace $\bar{\bar{Y}}_k$ everywhere with:

$$\bar{\bar{Y}}_{kw} = \frac{\sum_{i=1}^{k} w_i Y^*_i}{\sum_{i=1}^{k} w_i} \tag{4.9}$$

Making these substitutions, the estimates of α and β are now:

$$\hat{B}_{kw} = \frac{\sum_{i=1}^{k}[(i - \bar{k}_w) \times Y^*_i \times w_i]}{\sum_{i=1}^{k}(i - \bar{k}_w)^2 \times w_i} \tag{4.10}$$

$$\hat{\alpha}_{kw} = \bar{\bar{Y}}_{kw} - \hat{B}_{kw}\bar{k}_w \tag{4.11}$$

and the estimate of reliability is:

$$\hat{R}_{kw} = \begin{cases} 1 - e^{-(\hat{\alpha}_{kw} + \hat{B}_{kw}k)} & \text{for } k > 1 \\ 1 - e^{-\bar{\bar{Y}}_{1w}} = 1 - e^{-Y^*_1} & \text{for } k = 1 \text{ as before} \end{cases} \tag{4.12}$$

C. EXAMPLE OF THE WEIGHTED EXPONENTIAL REGRESSION MODEL

The following example is offered as a means of clarifying the application of this model.

Suppose that a system undergoes ten phases of testing and a phase is terminated upon occurrence of the third failure in each phase (i.e., $F_1=3$, $F_2=3$.... $F_{10}=3$). Suppose further that the weights given to each phase are as follows (See Table 1A):

TABLE 1A. EXAMPLE OF WEIGHT DATA

Phase	1	2	3	4	5	6	7	8	9	10
Weight	.03	.03	.03	.03	.03	.15	.15	.15	.20	.20

These weights have been arbitrarily selected for the purposes of this example. Actual calculation and/or selection of weights will be discussed in section D of this chapter.

Tables 2 and 2A represent the test data collected on this fictitious system and the resulting calculations based on this data:

TABLE 2. EXAMPLE PARAMETER CALCULATIONS BY PHASE

Phase(k)	# Trials to $F_k(x_{r_k})$	Y^*_k	$\bar{k}_w$	$\bar{\bar{Y}}_{kw}$	$\hat{B}_{kw}$	$\hat{\alpha}_k$
1	4	.333333	1	.333333	*	*
2	4	.333333	1.5	.333333	$.124 \times 10^{-5}$	.333331
3	7	.949995	2	.538888	.308333	-.077777
4	10	1.328967	2.5	.736408	.360356	-.164484
5	4	.333333	3	.655793	.099563	.357104
6	9	1.217856	10.5	2.248411	-.0933450	3.228533
7	4	.333333	9.333	1.610050	-.108354	2.621357
8	35	2.618203	9.0	1.862080	-.125571	2.992230
9	112	3.791201	11.25	2.809887	-.123688	4.201384
10	176	4.244785	11.0	3.096866	-.135948	4.592308

and reliablility estimates, $\hat{R}_k = 1 - e^{-(\hat{\alpha}_{kw} - \hat{B}_{kw}k)}$

TABLE 2A. EXAMPLE RELIABILITY ESTIMATES

Phase (k)	1	2	3	4	5	6	7	8	9	10
$\hat{R}_k$	.368409	.379257	.437538	.500470	.564331	.921049	.894045	.891848	.955032	.963680
R_k	.398418	.428109	.480793	.539243	.609949	.702683	.798124	.899963	.950990	.990040

* = not computed in the first phase. See equation (4.7).

D. METHODS OF WEIGHTING

1. Method One.

In the unweighted exponential regression model the estimate of β is the Gauss-Markov estimate when the variance in each phase is equal. When the variance is not equal from phase to phase "the variance of β is unnecessarily large." [Ref. 5]. This variance in parameter β accounts for the demonstrated higher reliability estimate variance evidenced in previous work [Ref. 1]. In order to diminish this variability each phase is systematically accorded a weight determined by the estimate of the variance of the phase:

$$w_k = \text{the weight allocated in phase } k = \frac{1/\hat{\sigma}_k^2}{\sum_{l=1}^{k} 1/\hat{\sigma}_l^2} \tag{4.13}$$

using weights derived in this manner, β_{kw} in equation (4.9) becomes:

$$\hat{B}_{kw} = \frac{\sum_{i=1}^{k} [1/\hat{\sigma}_i^2 (i - \bar{k}_w) \times Y^*_i]}{\sum_{l=1}^{k} [(i - \bar{k}_w)^2 \times 1/\hat{\sigma}_i^2]} \tag{4.14}$$

which is unbiased and has minimum variance among all unbiased estimators of β [Ref. 5].

Figure 2 demonstrates the effect of weighting the exponential regression model by this method.

As one can see, the weighted model more closely estimates actual reliability, particularly after the third phase of testing. Chapter VI contains more detailed comparisons of models.

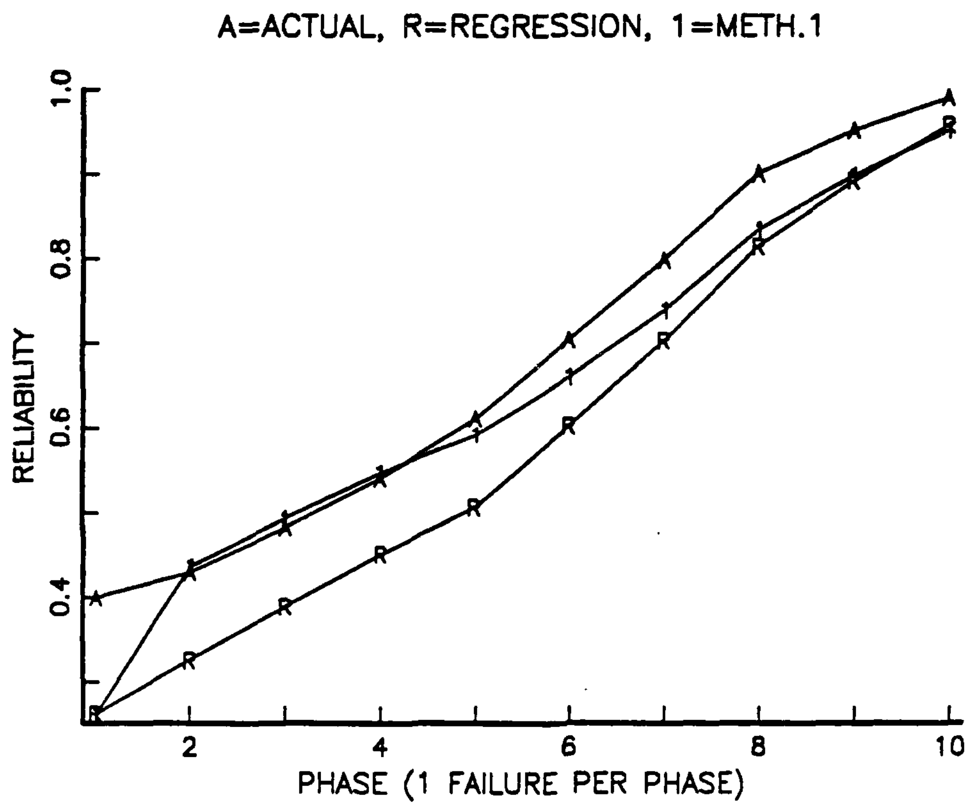

Figure 2. The Weighted Exponential Regression Model in Conjunction with Method One Weights.

2. Method Two

The second method of weighting applied to the exponential regression model was less theoretically derived. This method systematically allots more weight to the most recent phase. The rationale for the implementation of such a method is that since the aim of the development process is to improve the system, the reliability in the latter phases will be greater than in earlier phases. While this is not necessarily the case, the method none the less has intuitive appeal.

The weights used in this second method are calculated for each phase as follows:

$$w_k = \frac{\hat{\sigma}_k^2}{\sum_{i=1}^{k} \hat{\sigma}_i^2} \tag{4.15}$$

To see why this expression creates weights which increase with phase, recall that an estimate of the variance of the negative binomial distributed data is:

$$\hat{\sigma}_k^2 = \textit{an estimate of variance in phase } k = \frac{(F_k) \times (\hat{p}_k)}{(1 - \hat{p}_k)^2} \tag{4.16}$$

where:

F_k = # of failures in phase k, as before, and

$\hat{p}_k$ = The maximum likelihood estimate of the reliability in phase k.

Assume, as in our example in section C, that the number of failures in each phase is constant, then the term F_k may be ignored. One can readily see that as $\hat{p}_k$ increases, $\hat{\sigma}_k^2$ increases and therefore, w_k increases.

Figure 3 demonstrates the effect of weighting the exponential regression model by this method. The model weighted in this manner more accurately tracks actual reliability than both the unweighted and method one weighted model. More extensive comparisons are drawn in chapter VI.

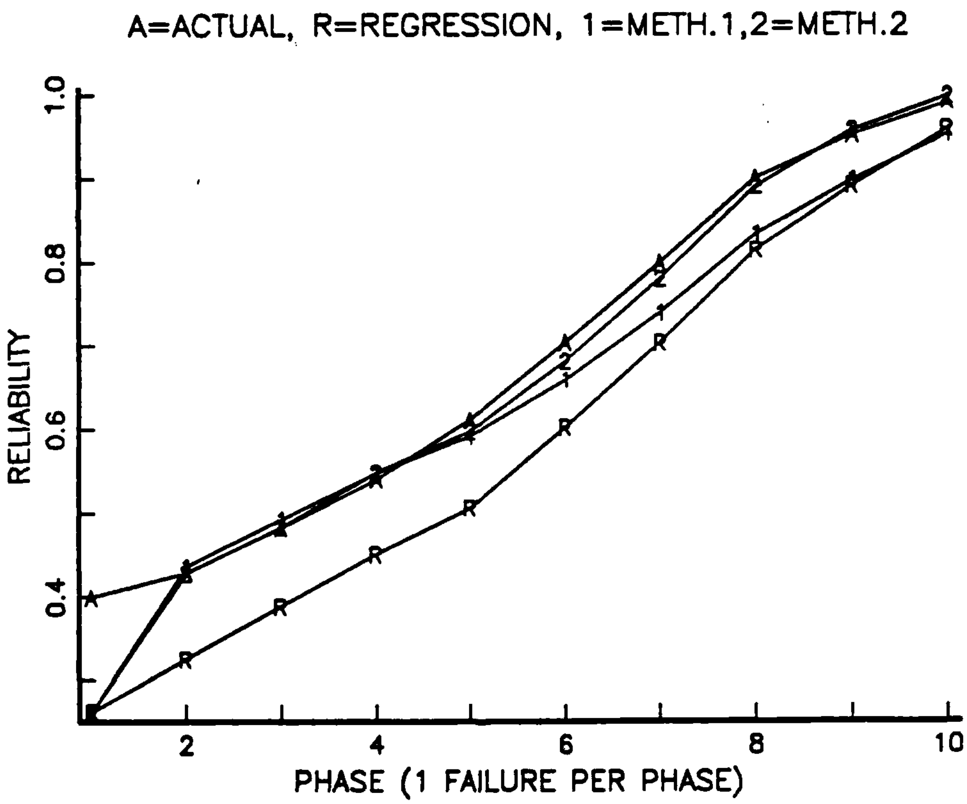

Figure 3. The Weighted Exponential Regression Model in Conjunction with Method Two Weights

3. Method Three

The third and final method of weighting the exponential regression model has no roots in theoretical mathematics. This "method" is simply to let the user select the amount of weight he desires to assign to each phase. His only constraint is that the sum of these weights over all phases equals unity. Selecting the weights for this method is currently analogous to specifying the parameters for use in failure discounting. Unless one possesses extensive knowledge and intimate familiarity with the system being evaluated as well as its developmental history, use of this method is not advisable.

To demonstrate the radical behavior of the model when this method of weighting is employed, five different cases of weights were evaluated. The weights for each case are listed in Table 3.

Figure 4 is an example of the behavior of the model when the weights listed as case 3 are employed. As one can see, this selection of weights resulted in an extremely poor performance of the model against the pattern of actual reliability. As with the previous two methods, further comparisons are contained in Chapter VI.

TABLE 3. SAMPLE METHOD THREE WEIGHTS

Phase(k)	case 1	case 2	case 3	case 4	case 5.
1	.014285714	.014285714	.03	.333333333	.0025
2	.014285714	.014285714	.03	.333333333	.0025
3	.014285714	.014285714	.03	.333333333	.005
4	.014285714	.014285714	.03	.333333333	.0025
5	.014285714	.014285714	.03	.333333333	.01
6	.014285714	.014285714	.15	.333333333	.025
7	.014285714	.014285714	.15	.2	.05
8	.2	.3	.15	.2	.1
9	.3	.3	.2	.2	.3
10	.4	.3	.2	.2	.5

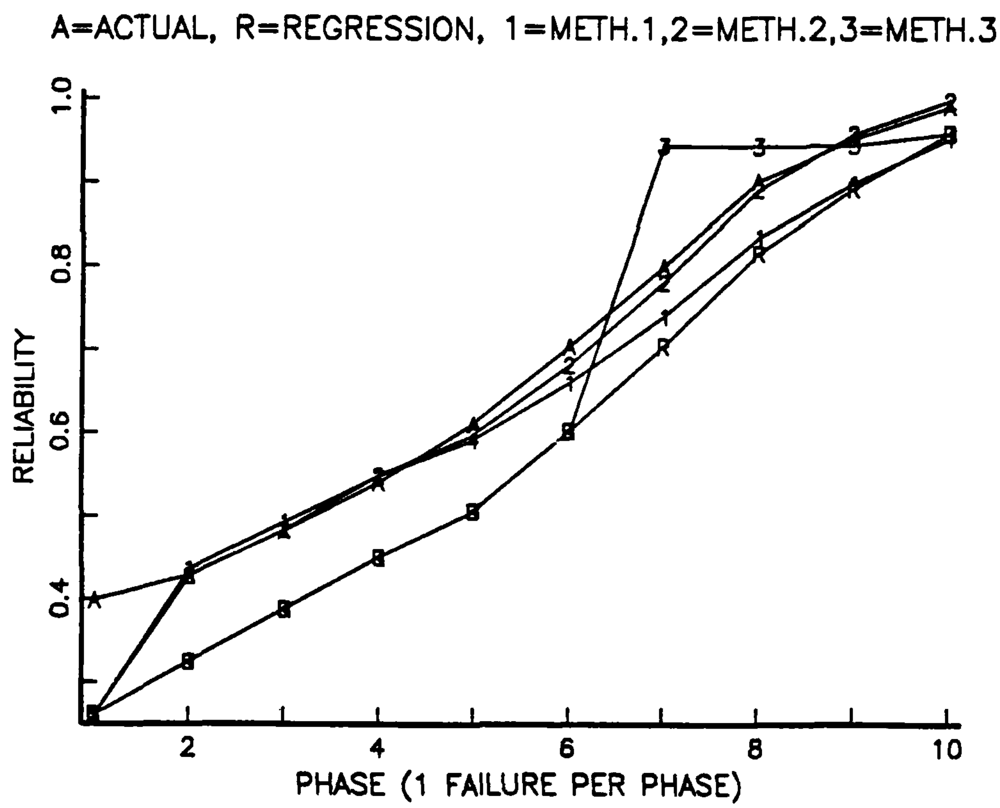

Figure 4. The Weighted Exponential Regression Model in Conjunction with Method Three Weights.

As a comparison, the weights for each of the methods depicted in Figure 4 are listed in Table 4.

TABLE 4. COMPARISON OF METHODS ONE, TWO AND THREE WEIGHTS OVER A TEN PHASE SIMULATION.

Phase	1	2	3	4	5	6	7	8	9	10
Method 1 Weights	1.0	.500	.166	.07583	.08663	.06247	.06827	.01891	.00318	.00982
Method 2 Weights	1.0	.500	.555	.530179	.297695	.279013	.192177	.405043	.705975	.695464
Method 3 Weights	.03	.03	.03	.03	.03	.15	.15	.15	.2	.2

The values listed are the amount of weight given to that particular phase when it is the current phase. Thus, for example, in Phase 9, method 1 allots .0031794 to the 9th phase and 1- .0031794 = .9968206 to the previous eight phases. Method 2 allots a much greater weight to phase 9, i.e., .705975, and only 1-.705975 = .294025 to the previous eight phases.

V. THE MAXIMUM LIKELIHOOD ESTIMATE WITH FAILURE DISCOUNTING IN THE TEST-FIND-TEST SCENARIO

A. DESCRIPTION

The conventional maximum likelihood estimate of reliability is:

$$\hat{R} = \text{\# of successes/\# of trials} \tag{5.1}$$

In order to use the estimator however, "...constant reliability, R, is required for each trial. Because the reliability at each phase R_k may not be constant with k; only the test data from the phase of interest may be used to estimate reliability" [Ref. 1:p. 22]. An excellent detailed description of failure discounting as applied to the test-fix-test scenario is contained in Ref.1:pp.13-21. This section primarily addresses the process when employed in conjunction with the test-find-test scenario.

The straight percent discounting method attempts to reflect improved system reliability by removing a fraction, F, of a failure's weight at an interval of every N trials. This sequence of N successful trials must occur in a follow-on phase of testing, after the components which were "found" to be causes of failure are modified or repaired. The idea here is that accumulation of subsequent testing without repeat of a failure for the same cause increases the confidence that the failure cause has been removed; therefore its weight in further estimations should be diminished. When using this method, the data is first adjusted and the model is applied to the modified data. The success of the model is wholly dependent on the correct adjustment of the data and hence the parameters chosen in calculating these adjustments. The equation used to compute the current value of an adjusted failure is:

$$\text{Adjusted failure}_{(j)} = (1-F)^{\text{int}(M/N)} \qquad (5.2)$$

where M is the number of successful sequential trials in follow-on phases for failure cause j and F and N are as above.

B. EXAMPLE

As an illustration of the method, consider the results of the following example. Suppose, as in our previous example, testing in each phase continues until the occurrence of the third failure. Further suppose the results of two phases of testing are as in Table 5.

TABLE 5. MLEWD EXAMPLE DATA

Phase	# Failures	# Trials to 3rd Failure	# Successes
1	3	5	5 - 3 = 2
2	3	6	6 - 3 = 3

Then applying equation (5.1), the maximum likelihood estimates without failure discounting are:

$$\hat{R}_1 = 2/5 = .4 \; ; \qquad \hat{R}_2 = 3/6 = .5 \qquad (5.3)$$

As one can see, the information obtained from the first five trials is disregarded in the calculation of the estimate of the reliability in the second phase. Continuing in this manner, the data in the first eleven trials will be ignored in computation of the third phase reliability. This practice is extremely inefficient by any standards.

In the test-fix-test scenario, [Ref.1:pp. 15-16] it is assumed that a design "fix" is implemented after each failure; in a test-find-test scenario, no modifications are assumed until a given number of failures is observed. The causes of the failures are merely noted for subsequent action. Since there is no justification for applying the discounting method until follow-on phases prove a cause corrected, different values of weights are assigned to the same sequence of successes and failures in these two scenarios. Tables 6 and 7 illustrate the application of the discounting method to both situations. In the calculations, the parameters N=3 and F=.25 are arbitrarily chosen. Unfortunately, in practice, they are often likewise selected.

TABLE 6

TEST-FIX-TEST DATA WITH DISCOUNTING

Phase	Trial	A		B		C		D	
		FAILURE CAUSE							
1	1	S	0	S	0	S	0	F	1
2	2	S	0	F	1	S	0	S	1
3	3	S	0	S	1	S	0	S	1
3	4	S	0	S	1	S	0	S	.75
3	5	F	1	S	.75	S	0	S	.75
4	6	S	1	S	.75	S	0	S	.75
4	7	S	1	S	.75	F	1	S	.5625
5	8	S	.75	S	.5625	S	1	F	1
6	9	S	.75	S	.5625	S	1	S	1
6	10	S	.75	F	1	S	.75	S	1
7	11	S	.5625	S	1	S	.75	S	.75

Notation: For each failure cause the attribute
S = Success F = Failure
is listed along with the corresponding weight of that attribute.

TABLE 7

TEST-FIND-TEST DATA WITH DISCOUNTING

Phase	Trial	A		B		C		D	
		FAILURE CAUSE							
1	1	S	0	S	0	S	0	F	1
1	2	S	0	F	1	S	0	S	1
1	3	S	0	S	1	S	0	S	1
1	4	S	0	S	1	S	0	S	1
1	5	F	1	S	1	S	0	S	1
2	6	S	1	S	1	S	0	S	1
2	7	S	1	S	1	F	1	S	1
2	8	S	.75	S	.75	S	1	F	1
2	9	S	.75	S	.75	S	1	S	1
2	10	S	.75	F	1	S	1	S	1
2	11	S	.5625	S	1	S	1	S	1

Testing in the Test-Find-Test scenario terminates after the 3rd failure. The straight percent discounting parameters are:

N = Discount Interval = 3

F = Fraction the failure is reduced = .25

Using the test-fix-test discounted data and MLEWD model produces the results shown in Table 8 upon completion of the eleventh trial.

TABLE 8. RESULTS OF THE MLEWD MODEL APPLIED TO THE TEST-FIX-TEST DATA

PHASE = FAILURE #	CAUSE	ADJ. FAILURE	ADJ. TRIALS
1	D	.75	1 .75 = 1.3333
2	B	1	1 1.0 = 1.0000
3	A	.5625	3 .5625 = 5.3333
4	C	.75	2 .75 = 2.6667
5	D	.75	1 .75 = 1.3333
6	B	1	3 1.0 = 3.0000

$\sum ADJ.\ TRIALS = 14.6665.$

Adj. trials = (the observed # of trials since the previous failure)/ (adjusted failure value).

and

$$\hat{R}_6 = \frac{(\sum ADJUSTED\ TRIALS) - (TOTAL\ \#OF\ FAILURES)}{(\sum ADJUSTED\ TRIALS)} = .5909 \qquad (5.4)$$

As one can see, this estimate is higher than that predicted after the eleventh trial (second phase; eq. 5.3) using the MLE without discounting. Since it takes into account 5 additional data points it is considered to be a superior estimate...provided the parameters were correctly chosen.

The results of the test-find-test-scenario after the eleventh trial are as shown in Table 9.

TABLE 9. RESULTS OF THE MLEWD MODEL APPLIED TO THE TEST-FIND-TEST DATA

PHASE	CAUSE	ADJ. FAILURE	ADJ. TRIALS
1	D	1.0	1/1.0 = 1.0000
1	B	1	1/1.0 = 1.0000
1	A	.5625	3/.5625 = 5.3333
2	C	1.0	2/1.0 = 2.0000
2	D	1.0	1/1.0 = 1.0000
2	B	1	3/1.0 = 3.0000

$\sum ADJ.\ TRIALS = 13.3333.$

$\hat{R}_2 = .5499$

As a comparison, the reliability after the second phase of testing in the test-fix-test scenario would be zero since there were two failures in two trials.

The results seem to indicate that the estimate of reliability of a system or equipment will grow more quickly appeal as it seems likely that if failure causes are corrected immediately they are else like to be responsible for further failure. These results additionally demonstrate that the use of discounting has the desirable characteristic of producing higher estimates of reliability than the conservatively biased MLE without discounting [Ref. 3:p. 34].

VI. MODEL COMPARISONS

A. INTRODUCTION

In sections B through F of this chapter, the performance of the unweighted exponential regression model will be compared to that of the weighted model used in conjunction with weighting methods one and two. The employment of method three will be discussed in Section G. The performance of the MLEWD will additionally be discussed where appropriate. For the purposes of this evaluation patterns VI, VII and VIII will be discussed as a group in the category, Constant Reliability. Patterns IV and V will be similarly grouped under the title Rapid Reliability Growth, while pattern I, Convex Reliability, pattern II, Decreasing Reliability and pattern III, Intermittent Reliability will be evaluated individually. All discussion is in regard to test-fix-test scenarios to facilitate reference to previous work.

B. CONSTANT RELIABILITY PATTERNS

Figure 10 [Ref. 2:p. 32] illustrates the performance of the MLEWD model against representative constant reliability pattern VI. No failure discounting was implemented in this case. The MLEWD model performed better than either the weighted or unweighted regression models in all three constant reliability patterns, although its superiority diminished with lower levels of constant reliability. This was expected since, as indicated in Chapter V, the underlying assumption of the MLE is one of constant reliability.

Figure 5 is an illustration of the unweighted and weighted exponential regression models also against constant reliability pattern VI. Regardless of the level of constancy, the unweighted model consistently underestimated reliability while the weighted model overestimated it. In all patterns, the model weighted using method 2 (i.e., more weight to the most recent phase) produced better results than when method 1 (i.e., more weight to less variable phases) was employed.

C. *RAPID RELIABILITY GROWTH*

Figure 6 depicts the performance of the models when applied to Pattern V. This pattern is one in which "actual" reliability achieves its greatest value (approximately .9) early in the testing process (phase 3) and remains there throughout the remainder of the testing. Pattern IV is, in all ways, similar to pattern V with the difference being that it achieves the value of approximately .99 in phase 3. Both versions of the weighted model and the unweighted model underestimated reliability during its growth phases although

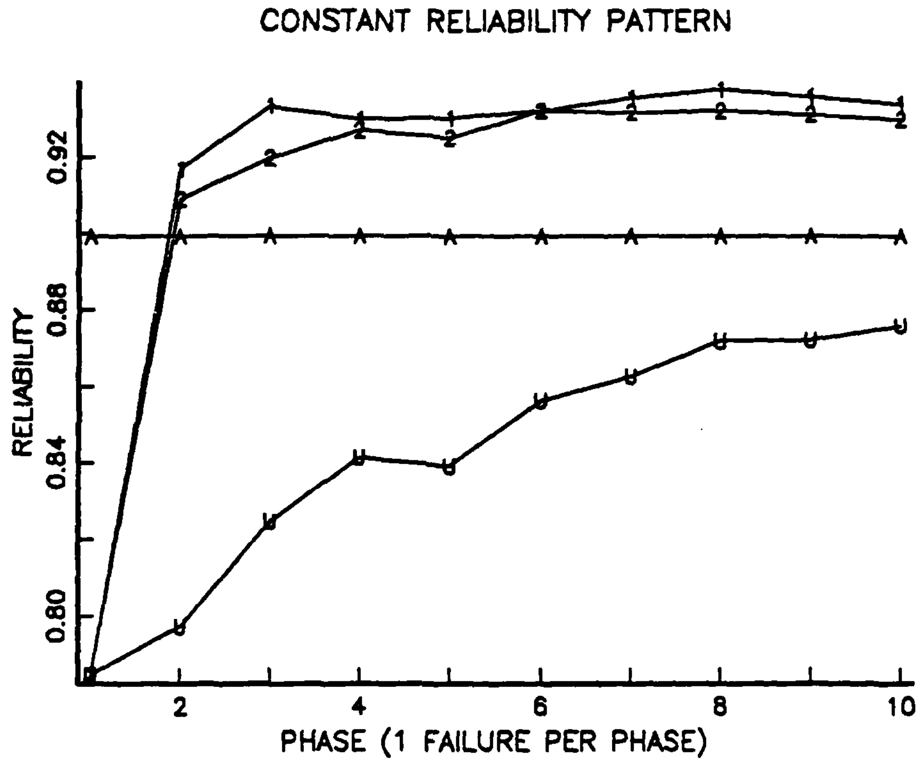

Figure 5. Weighting Methods One and Two and the Constant Reliability Pattern

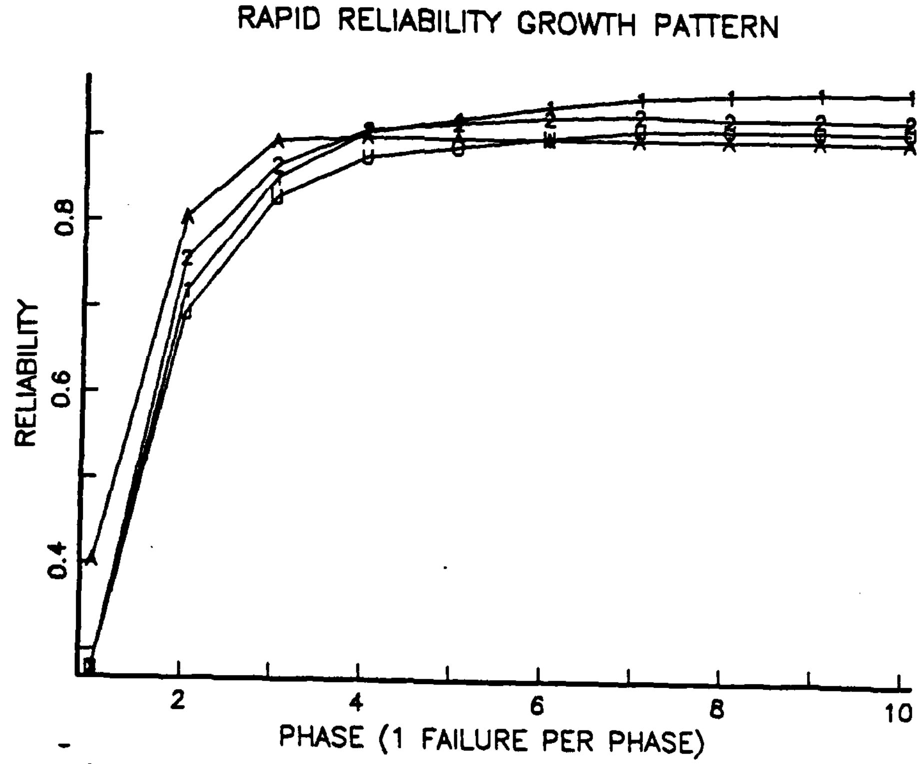

Figure 6. Weighting Methods One and Two and the Rapid Reliability Growth Pattern

the weighted models more accurately tracked the process. As with constant reliability, the model weighted by Method 2 outperformed the model when weighting Method 1 was employed. Also similar to constant reliability performance results, both versions of the weighted model produced higher estimates than the unweighted model over all phases. Given this underlying pattern, if one is concerned with tracking the initial phases of testing, the weighted model in conjunction with Method 2 is recommended as it best captures the growth portion of the development process. The unweighted model in this case seems to best capture the constant reliability portion of the development although its superiority is minimal. Figures 13 and 14 [Ref. 2:pp. 36-37] illustrate the performance of the MLE both with and without discounting. In both cases, the exponential regression model outperforms the MLE over all phases.

D. CONVEX RELIABILITY GROWTH

This pattern illustrated the most dramatic support for application of weighting to the exponential regression model. Figure 7 depicts the substantial improvement in reliability estimation when weighted Method 2 is employed. Use of Method 1 also produced superior results to the unweighted model although these were not as dramatic, particularly in the latter phases of testing. Both versions of the weighted model seemed to capture the pattern of

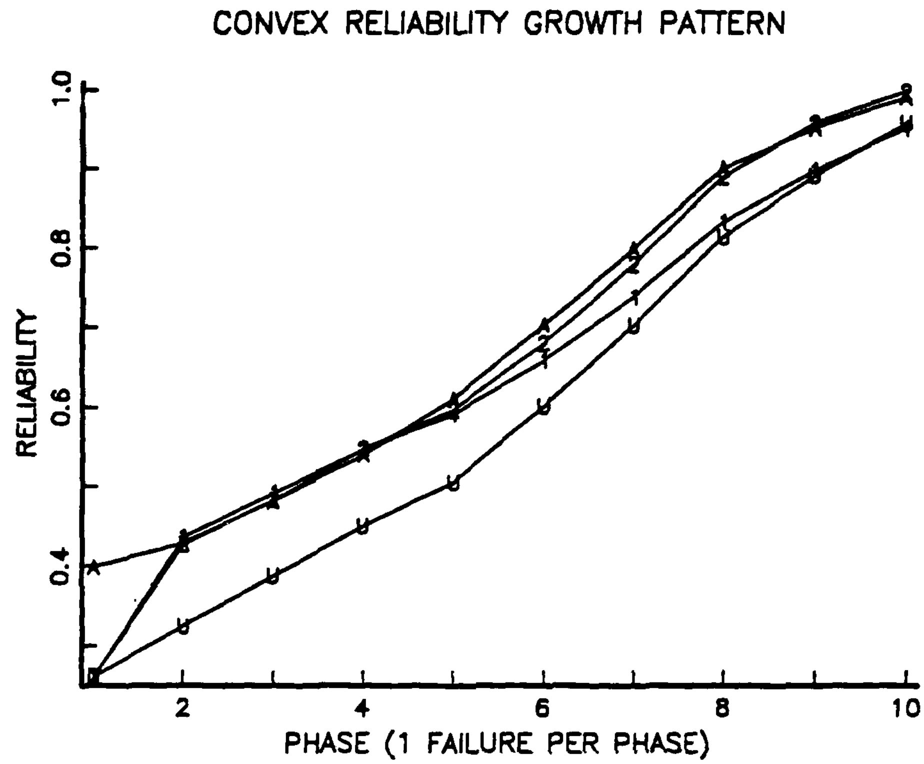

Figure 7. Weighting Methods One and Two and the Convex Reliability Growth Pattern

growth as early as phase 2. No earlier improvements can be anticipated as all three versions of the regression model require at least two phase of testing to perform a linear regression.

Figure 23 [Ref. 2:p. 46] demonstrates the poor performance of the MLE when no discounting is applied.

These results are not surprising as the underlying assumption of constant reliability in the case of the MLE is violated here. A dramatic improvement as seen in Figure 24 [Ref. 2:p. 47] when discount parameters, F=.75 and N=6 are applied to the data. The parameters were selected after a good deal of trial and error simulation, however, and no explanation as to why this choice of parameters was effective can currently be offered. Since the luxury of simulation is not often available in practice, and the weighted model in conjunction with Method 2 outperforms the other models, it is recommended for use while the underlying reliability pattern is suspected to be convexly increasing.

E. DECREASING RELIABILITY

Figure 8 indicates that the same general previous observations can be made with regard to the performance of the models in the case of decreasing reliability. The unweighted regression model produced estimates which are everywhere below those of the weighted model regardless of the weighting method employed. Additionally, the weighted models seem to more accurately capture the changing growth pattern. The unweighted model is most accurate when actual reliability decreases to a low value however this is primarily due to the fact that the unweighted model consistently tends to underestimate actual reliability and

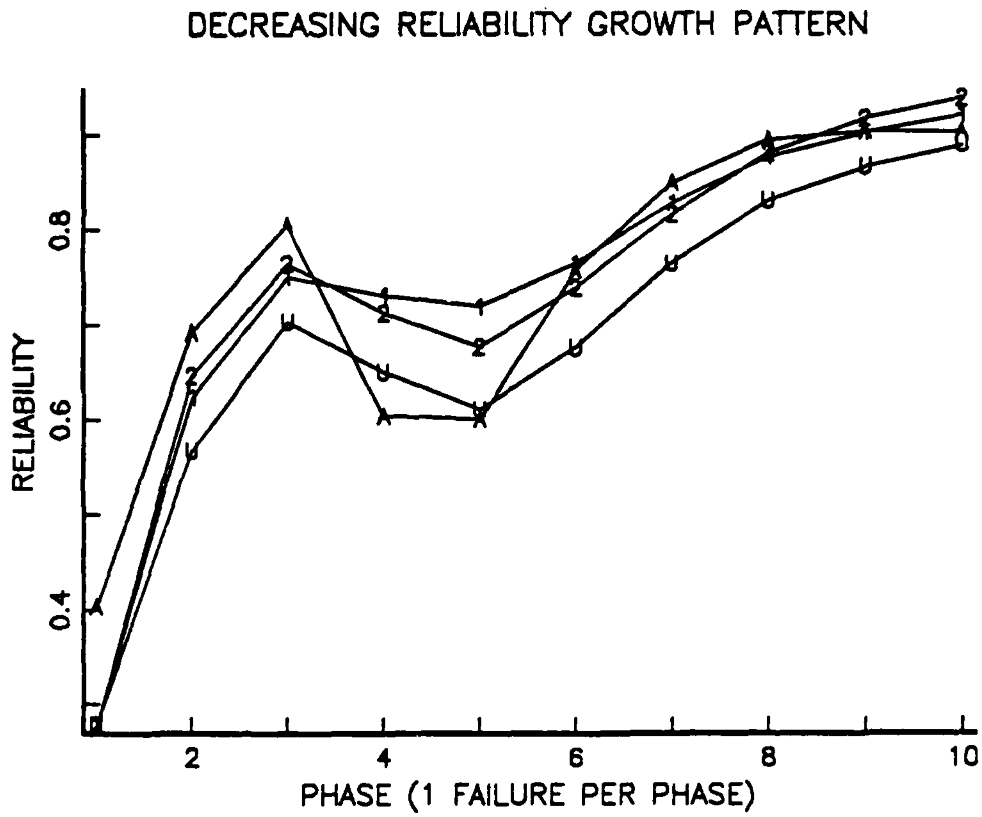

Figure 8. Weighting Methods One and Two and the Decreasing Reliability Growth Pattern

is less responsive to changes in the actual growth pattern. Therefore when actual reliability dipped and the already low unweighted model did not respond, the result was a fairly accurate estimate. As in previous patterns, the model weighted by giving most weight to the most recent phase estimate produces the most responsive results. For this reason, this model would be recommended in this case.

Figures 17 and 18 [Ref. 2:pp. 40-41] demonstrate the inability of the MLE model to capture a decreasing reliability pattern whether failure discounting is employed or not.

F. INTERMITTENT RELIABILITY GROWTH

The Intermittent Reliability Growth pattern (Figure 9) can be described as one in which reliability grows fairly rapidly, remains constant for several phases and then resumes growth. Such a pattern would occur if intended improvements to a developing system were ineffective for a period of time before discovery of beneficial change was implemented. As in all previous patterns, the unweighted model produced more conservative estimates than both versions of the weighted model. Also as before, the model weighted by Method 2 was most responsive to changes in the reliability pattern. This is particularly evident in phases 5 and 6 where it dips below the Method 1 estimate in an attempt to recognize the period of constant reliability. All three versions of the exponential regression model outperformed the MLE model regardless of whether failure discounting was employed. Figures 20 and 21 [Ref.2 :pp. 43-44] reflect this.

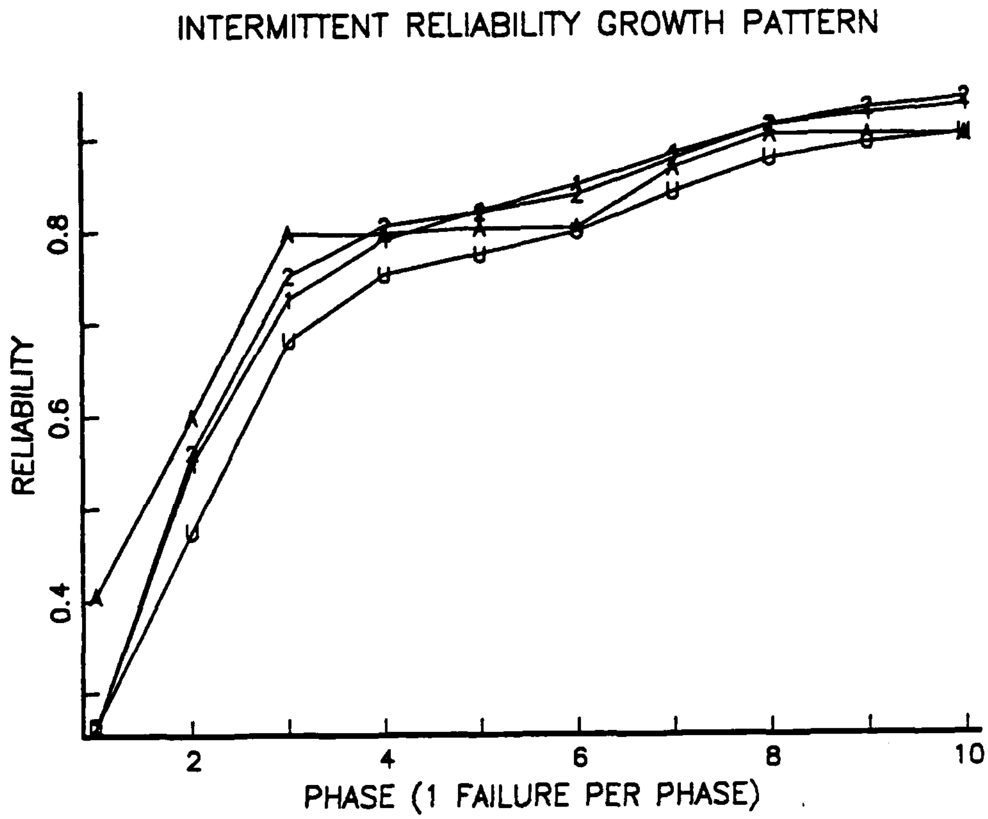

Figure 9. Weighting Methods One and Two and the Intermittent Reliability Growth Pattern

G. THE WEIGHTED MODEL IN CONJUNCTION WITH METHOD 3 WEIGHTING

Weighting Method 3 is the application of user selected weights to the exponential regression model. Figures 10 - 14 corresponding to representative examples of constant, rapidly increasing, convex, decreasing, and intermittent reliability respectively, demonstrate the sensitivity of the model to the choice of weights. In every case the weighted regression model identically tracks the unweighted model until the user influences the process by applying a weight to a phase. For example, when the case 1 weights are employed, the user has given equal weight to the first seven phases of testing. This is equivalent to not weighting the model at all. Therefore, one would expect the unweighted model to produce identical results to this version of the weighted model. That this is in fact occurring, is most clearly seen in Figure 10. Tracking the curve labeled "1", (corresponding to case 1, Weights Table 3), one can see it is identical to the unweighted growth curve until Phase 7 after which it abruptly increases. Similar departures from the unweighted curve are seen for the other four cases of user selected weights. These results are welcome in that they substantiate the programming of the weighting process. They are disappointing however, in that, as with the MLEWD model, the response of the exponential regression model seems to be very sensitive to the choice of weights. Unlike the MLEWD model though, there are two systematic means of selecting weights which consistently produce accurate results (i.e., methods 1 and 2). It is recommended that these two weighting methods be employed unless the user is intimately familiar with the development process and has the unique ability to reflect his knowledge in the choice of weights.

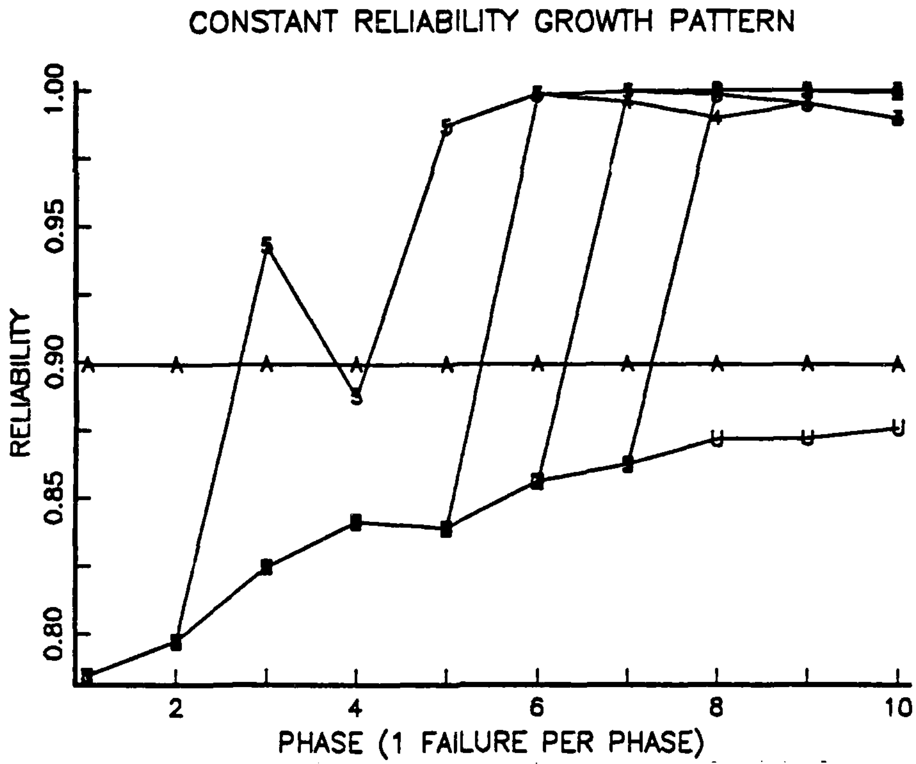

Figure 10. Method Three Weights and the Constant Reliability Growth Pattern

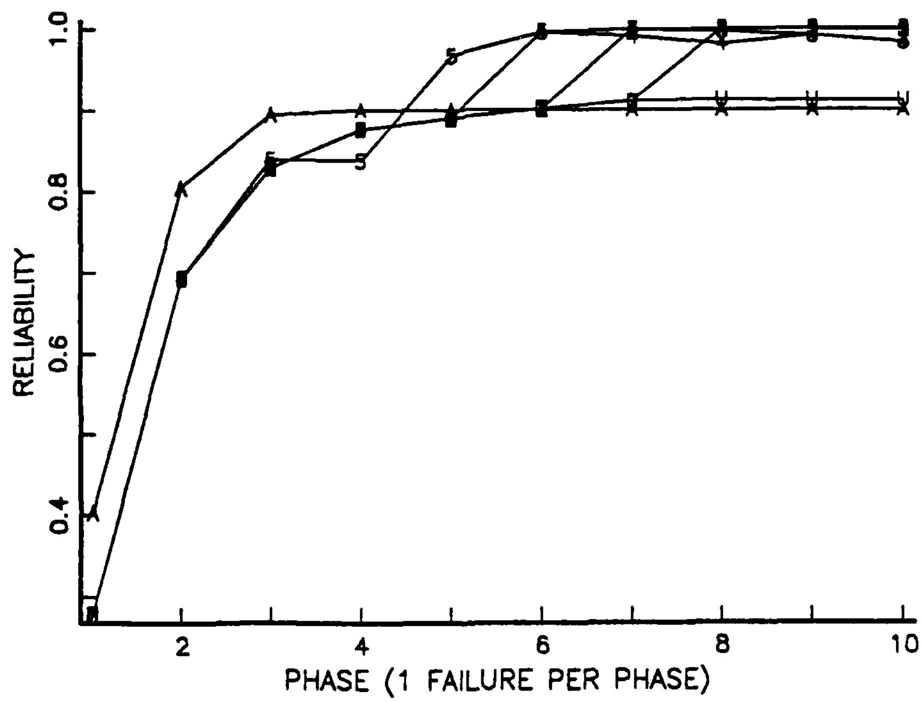

Figure 11. Method Three Weights and the Rapid Reliability Growth Pattern

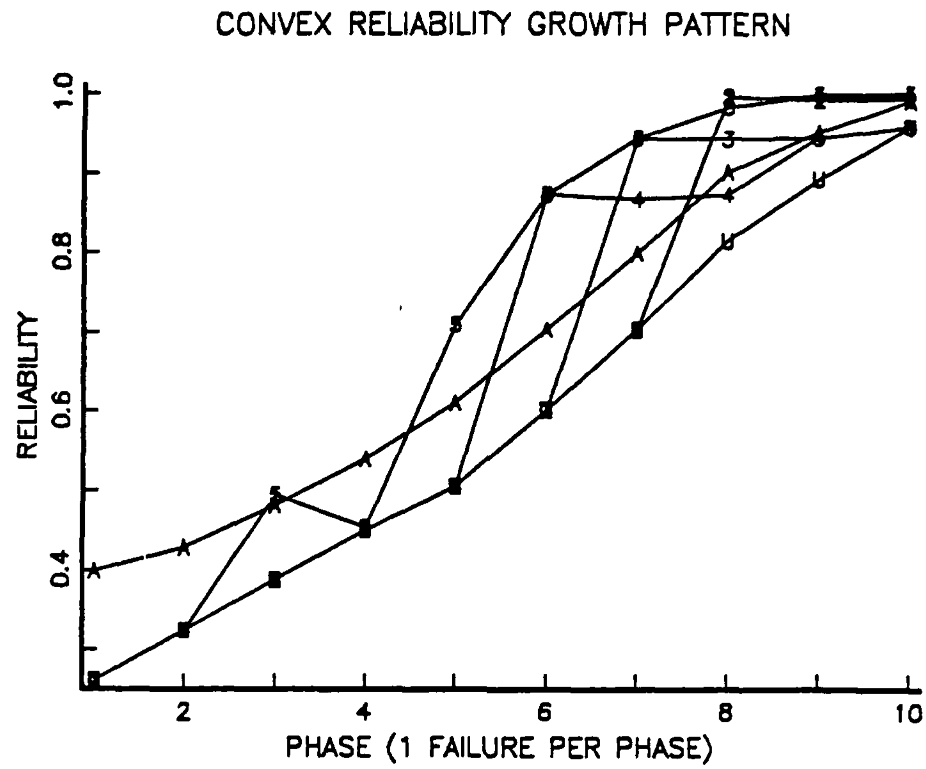

Figure 12. Method Three Weights and the Convex Reliability Growth Pattern

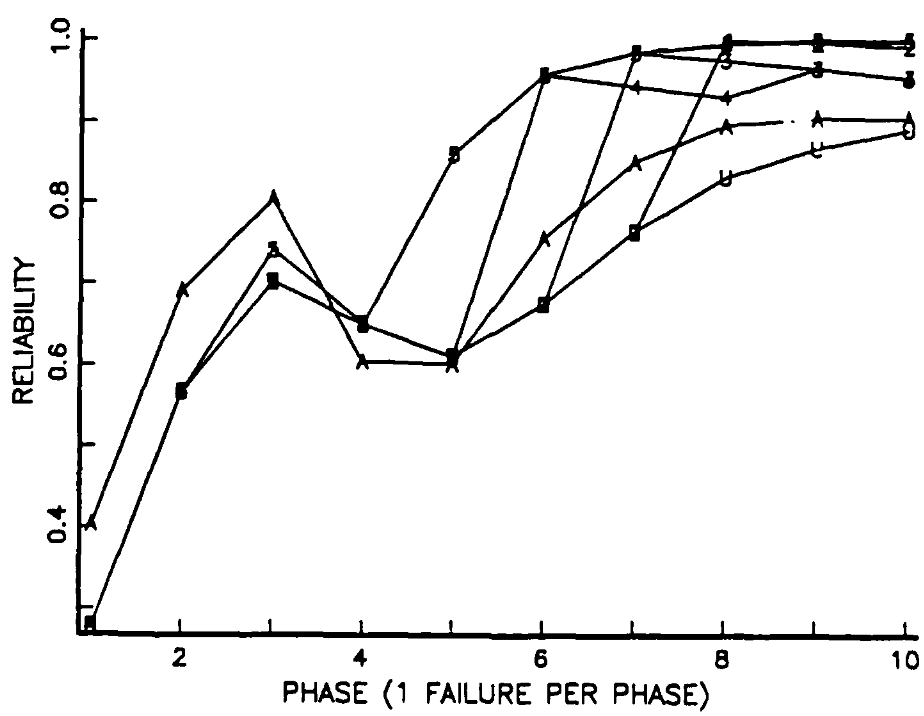

Figure 13. Method Three Weights and the Decreasing Reliability Growth Pattern

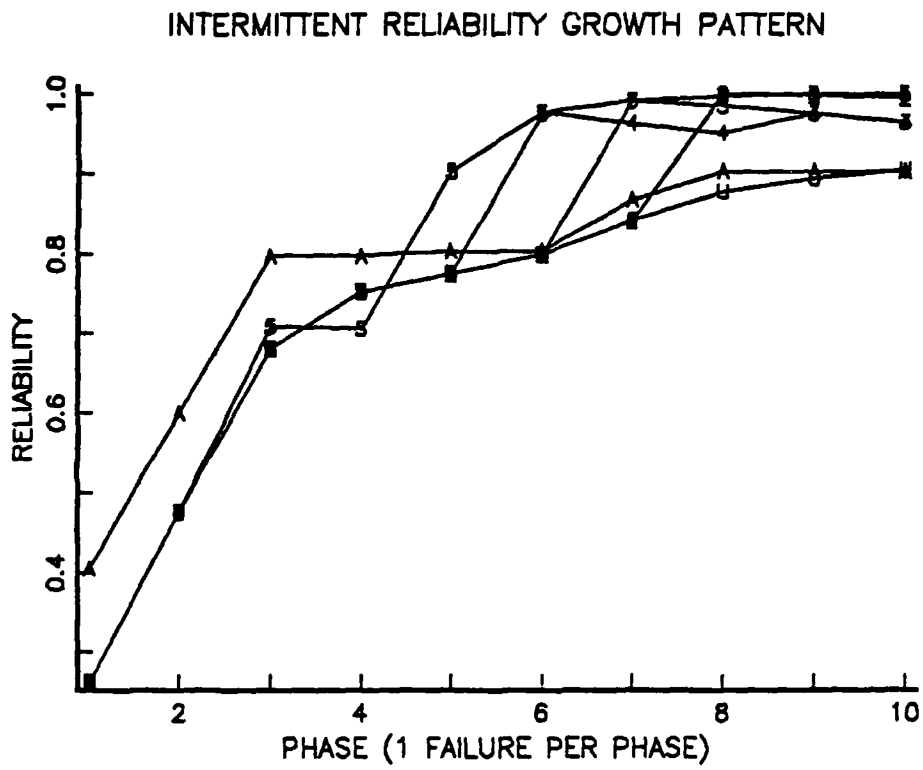

Figure 14. Method Three Weights and the Intermittent Reliability Growth Pattern

VII. SUMMARY, CONCLUSIONS, RECOMMENDATIONS

A. SUMMARY

Captain Drake created a FORTRAN program which simulated actual reliability patterns and evaluated the performance of three reliability growth models against these patterns. His work indicated that the MLEWD model was effective against all patterns when used in conjunction with the correct discounting parameters. He also found that the exponential regression model likewise tracked all actual patterns and was relatively insensitive to the discounting parameters. This model, was however, more variable than the MLEWD model.

Captain Chandler modified Captain Drake's program to produce several additional actual reliability patterns and subsequently evaluated both models against these patterns. His results demonstrated that the MLEWD model was incapable of tracking declining reliability and was only superior to the exponential regression model when actual reliability was constant; a phenomenon which, by design, rarely occurs in the development process.

The objective of this thesis was to improve the exponential regression model by applying weights to the model at each phase. The intent was to produce an accurate means of estimating changing reliability without burdening the user with selecting discounting parameters.

Three methods of weighting were derived. The first method gives low weight to the most variable estimates of reliability, while the second weights most recent results more heavily. With both these methods, the FORTRAN program systematically computes these weights at each phase. In method 3, the user is required to input values of weights for each phase of testing. Use of this method produced results which were very sensitive to the weights chosen and presented the user with the dilemma of selecting critical input parameters without any guidance. Since this is the very situation which the employment of weights was derived to avoid, this method is not recommended.

B. CONCLUSIONS

Regardless of the underlying actual reliability pattern or the method of weighting, the weighted exponential regression model produced higher estimates of reliability than the unweighted model. Since the unweighted model generally underestimates actual reliability this is considered to be a desirable characteristic. Both the weighted and unweighted model produced results comparable or superior to the MLEWD model against all variations of the actual reliability pattern with the exception of the case of constant reliability. In this case, the MLEWD would be recommended.

In all other cases, the regression model weighted by Method 2 seems to be most responsive to changes in actual reliability. Additionally, it produced more accurate estimates than the model weighted by either Methods 1 or 3. In the case of convex reliability Method 2 weights are a clear choice over the unweighted model as well. When a period of decreasing reliability is suspected in the development process, the Method 2 weights are also recommended unless one is concerned with the magnitude of the decrease as opposed to the trend of the pattern. In this case the more conservative unweighted model is recommended. When estimating the reliability of the intermittent and rapidly increasing patterns, the Method 2 weighted model most accurately captured the growth phases of reliability but were less accurate than the unweighted model in the final phase of testing although the differences in estimates here were minimal. Based on these conclusions, it is recommended that if a user has little or no knowledge of the actual reliability growth of a developing system or equipment, he would be wise to select the exponential regression model in conjunction with Method 2 weights to estimate the reliability growth curve.

As a final conclusion to this study, implementing the unbiased estimator with minimum variance, Y_k^* in all versions of the exponential regression model resulted in an improved reliability estimate over the models in conjunction with $\overline{Y}_k$.

C. RECOMMENDATIONS FOR FURTHER STUDY

The following are recommendations for further study.

1. Since a large segment of the commercial world collects its reliability data in terms of mean time between failures (MTBF's) it is highly recommended that a simulation to analyze continuous data be derived.

2. Presently, straight percent failure discounting has shown some promising results when the discounting parameters are correctly chosen. Development of guidelines for selecting these parameters would certainly be of value in the employment of the MLEWD model. A difficulty in studying these parameters is that they cannot be altered from phase to phase or varied with failure cause in the current version of the program.

3. As with failure discounting, the employment of user selected weights might prove beneficial if guidelines could be developed to aid in their selection. A more extensive analysis of this weighting method is recommended.

APPENDIX A

USER'S GUIDE TO DISCRETE RELIABILITY GROWTH (DRG)

1. Introduction
2. The DRG Exec File
3. The Input Data File

APPENDIX A: USER'S GUIDE TO DISCRETE RELIABILITY GROWTH (DRG)

1. Introduction

In order to use the Fortran program, DRG, the user must possess three files:

1. Input_ data A1
2. DRG Fortran A1
3. DRG Exec A1

A sample of each of these files is contained in Appendix B along with sample output. The input file and the exec file may be tailored to the user's needs. In its current form, the exec file produces a large degree of intermediate calculations for both the DRG Fortran program and Captain Chandler's program, JIMC Fortran A1. A copy of this program is also contained in Appendix B. These calculations may not be of interest to the user and may be eliminated with no detrimental effect to the program. A detailed explanation of each file definition is contained in section 2 of this appendix.

The difference between the two versions of the Program is that JIMC Fortrans retains the ability to employ the weighted average estimate model and uses $\tilde{\bar{Y}}$ vice Y^* in the calculations of all versions of the exponential regression model. (see chapter III for a discussion of the motivation for altering this parameter which is discussed in

Section 3 para 12. In all other ways, the input files for these two programs are identical.

2. <u>The DRG Exec File</u>

This file contains all the requisite file definitions and commands to run either DRG Fortran A1 or JIMC Fortran A1. To indicate which of these programs is desired, the user must alter the third line of the file so that it reads, **&FN=DRG** or **&FN=JIM** respectively. Once this has been done, the user simply types **DRG** or **JIMC** while in CMS to execute the program.

Of the remaining lines, only those beginning with the word **FILEDEF** should be altered or eliminated. All other lines contain commands pertaining to the execution of the program. The first FILEDEF line currently reads **FILEDEF 10 DISK INPUT1 DATA A1**. The "1" in the filename indicates that this data file produces actual reliability growth pattern 1 described in this thesis. Eight patterns and input files have been established for each program. These input files may be duplicated as described in Section 3 using the corresponding pattern parameters in Ref. 2 if the user does not have them readily available. This FILEDEF may not be eliminated from the exec file, however the "1" may be changed to any integer up to and including "8" for use with DRG Fortran A1. The integers 9 through 16 correspond to the same patterns when executing JIMC Fortran A1. This numbering convention is adhered to with the remaining

FILEDEFs. Since a filename is only permitted to be six characters in length, whenever necessary, it is truncated to include the integers discussed. For example, input 1Ø is an unacceptable filename therefore the "T" is dropped from the word "input" to allow "inpu1Ø."

The next two FILEDEFs have the filenames A1 and A9 respectively. The first corresponds to the "actual" reliability pattern (pattern 1) produced by the DRG program while the second corresponds to the same pattern when JIMC Fortran A1 is run. These files should contain identical output. Both are kept for convenience so that if for instance, the user runs DRG with pattern 1 input and then JIMC with pattern 2 input he will still retain the initial "actual" reliability file, i.e., it will not be overwritten. These two files were both devised solely for plotting purposes and may be eliminated with no disruption to the program. The information contained in these files is duplicated in PRELIAB and JRELIAB Listing respectively.

PRELIAB LISTING A1 contains the primary comprehensive output for the DRG Fortran program while JRELIAB contains similar information for JIMC Fortran A1. These files consist of a model parameter summary, a comparison of the mean predicted reliability for each model to the actual, the estimate standard deviation and a 95% confidence interval for each model. Also contained in these files is a recapitulation of results so that each model may be compared to all others. These FILEDEFs should not be eliminated from the exec file.

JThesis and **PThesis** are the filenames corresponding to the intermediate summary output produced by JIMC and DRG Fortran respectively. These files contain a phase by phase listing of failures and failure causes for up to 5 simulations. This output may be "turned on (or off)" by placing a 1 (or Ø)" in the appropriate line of the input file. See section 3 para 12 for details. These FILEDEFs should not be eliminated from the exec file.

PMATRIXA and **JMATRIXA** contain the working "A" matrix for each of the programs. The working A matrix contains such information as the probability of success for each failure cause, the number of trials to failure for each cause, the system cause of failure, the phase number, and, in the case of JMATRIXA, the adjusted number of trials and adjusted number of failures. These FILEDEFs may be eliminated if desired.

PREGMAT and **JREGMAT** contain the parameters computed in the REG, WREG1, WREG2, and WREG3 arrays as described on page 2 of the program heading, (Appendix B, section 3). These matices pertain to the exponential regression and Weighted exponential regression models. These files are not required.

Ystar LISTING is produced only by DRG Fortran A1. It currently lists (arbitarily) the first 219 values for the tenth phase of testing. It is included merely as a verification of the implementation of this parameter. This FILEDEF may be eliminated.

TRIALS DATA A1 is also only produced by DRG Fortran A1. It lists the adjusted trials to failure for each phase. In addition, the weights computed for use by methods 1 and 2 are contained here. This FILEDEF is not required.

EST OUT A1 is produced only by JIMC Fortran A1 and contains each phase estimate generated by the Woods Weighted Average Estimate Model for up to the first 5 simulations run. The remaining FILEDEFs with File Type "OUT" contain similar information generated by the filename models. A file name beginning with the letter "J" corresponds to output produced by JIMC Fortran A1, while a file name starting with the letter "P" originated from DRG Fortran A1. These FILEDEFs should be retained.

All of the remaining FILEDEFs correspond to files generated solely for plotting purposes. Each contains the mean reliability estimates of each phase in the Filetype "NUM" file and the corresponding standard deviation of these estimates in the Filetype "SDV" file. The information in these Files is duplicated in PRELIAB and JRELIAB LISTING. If the user is not interested in graphing results, these 24 FILEDEFs may be eliminated. As explained earlier, the integers in the filenames of these files correspond to the underlying actual reliability growth pattern.

3. <u>The Input Data File</u>

These instructions should be used in conjunction with a sample input file (See Appendix B, section 2) to aid in understanding. The easiest method for preparing an input file is to edit an existing input file. Due to the formatting of the "READ" statements in the simulation, it is imperative that all inputs be entered in the correct sequence. The simulation is built to read input from device number 10.

The following steps should be allowed in order to produce an acceptable input file. All entries must be on a separate line in the input file although they may be anywhere in the line as long as the data entry is the first item encountered.

1. Determine how many failure causes will be allowed in this simulation. This number must be an integer greater than or equal to one. There is no set limit on how large a number is possible. The capacity of the machine on which the program is being run will have some effect. Enter this number on the top line.

2. Determine how many test phases are desired. Again, this number must be an integer greater than one. Enter this number on line 2.

3. If the fixed phase reliability mode is desired than enter a 1 on line 3. If the constrained random growth mode is required than enter a 0 on line 3.

4. Enter the number of failures that will be allowed in Phase 1 on line 4. This number must also be an integer. A test-fix-test scenario would have one failure per phase, for example. Repeat this process on successive lines until you have entered the number of failures allowed for each phase that will be tested. Remember, if you defined the test as being 10 phases, then you should have 10 separate entries, each on its own line, for this step.

5. If the constrained random growth option is selected (you should have entered a 0 at line 3) then you must now enter the probability of success due to each failure cause for the first phase. This step should contain as many lines as the number of failure causes you identified in Step 1. The probability of success due to a failure cause is simply the probability of the failure cause occurring subtracted from one.

6. If the fixed phase reliability option is selected (you should have entered a 1 at line 3) then the process of entering the probabilities of success is a little more involved. Fixed phase reliability means that one is controlling the actual system reliability at each phase of the test. Since this system reliability is merely the product of the probabilities of success of all the failure causes at each phase then the user must enter these probabilities. These probabilities are entered by failure cause for each phase. If there are two failure causes and 3 phases in a test then the first entry will be the probability of success due to failure cause 1 in phase 1; the next entry will be the probability of success due to failure cause 1 in phase 2 and then failure cause 1 in phase 3. After failure cause one has been entered for all three phase then failure cause 2's probabilities of success should be entered by by phase. Remember that each data entry must be on its own separate line. If X is the number of failure causes and Y is the number of test phase then this step should result in XY total data input lines. This number does not alter if more than one failure is permitted in a phase.

7. The next item that must be entered concerns use of the standard failure discount method. Even if you desire to use the C.L. discount method or if you do not desire to discount previous failures at all you must still place a value in this line. This line requires you to enter the discount interval or the number of successful trials that must occur between applications of the standard discount method. This number should be an integer.

8. The next item required is the discount fraction. This value also applies to the standard discount method. If you do not want to discount previous failures then your should enter 0.0 on this line. If you desire to discount previous failures by 50 percent each time the discount method is applied then you should enter 0.50 on this line. If you are using the C.L. discount method, you must still enter a value here, although it will not be used by the models in estimating reliability.

9. The next required entry is the random number seed for random number generator. Any number greater than zero and less than 2^{31} will suffice.

10. The FRIMP must be entered next. This value is only used if the constrained random growth mode is selected at line 3. This number must be between 0 and 1 and represents the fraction by which reliability will improve from phase to phase. It is applied to the probabilities of success of the failure causes each time they cause system failure in a phase. This method is intended to represent repairs or improvements in the system during the test. An entry of 0 will result in constant reliability while entries close to one will result in rapid reliability growth. Even if you are using the fixed phase reliability option you must still enter a value here although it will not play any role in the simulation.

11. The next item that must be entered is the number of replications desired. For the purposes of the thesis associated with this paper 500 replications were done for each reliability growth pattern.

12. The next 7 (8, for use with JIMC Fortran A1) lines of required input deal with intermediate and specified output. They are all binary (0 or 1) option statements. The first addresses intermediate output. If intermediate phase by phase data is desired then the user should enter a 1 here. If intermediate output is not desired then enter a 0. This output will get voluminous rather quickly, particularly if a large number of relications is requested. The remaining options deal with the estimates generated by each model at each phase. The final output (which will be given regardless of the options chosen here) represents the average of all these estimates. If phase estimates are desired then a 1 should be entered; if not then enter a 0. The order of entry is weighted average model (for JIMC Fortran program only), MLE with failure discounting model, MLE single phase model, exponential regression model, and weighted exponential regression methods 1 through 3. Again, each data entry must be on a separate line.

13. The next required entry is the failure discounting option. If you desire to use the standard discount method then enter a 1. If you desire not to discount at all enter a 1 and make sure you have entered 0.0 as instructed at Step 8 above. If you desire to use the C.L. method of failure discounting then enter a 2 in this space.

14. Next enter the value of the C.L. method parameter (the confidence interval). This number should be between 0 and 1 and will typically be in the range of 0.8 to 0.99.

15. The next item that must be provided is the C.L. discount interval. Normally, the C.L. method does not use a discount interval (defined similar to the definition of a discount interval for the standard discount method) but in the majority of cases applying this method with some type of specified interval will lead to better results. These last two items must be entered even if one is using a alternate method of discounting. The other method will be applied but values are required due to the particular formatting of the simulation.

16. The final entries that must be made are the weights to be accorded each phase of development. Enter any fraction between zero and one for each phase on a separate line. Remember the sum of these fractions must equal one. These entries are required regardless

of whether the user desires to apply weighting Method 3 or not. Note: Giving equal weight to all phase is equivalent to not weighting and will produce results identical to the exponential regression model.

If the input file is established consistent with the format outlined above and with the sample input file provided in Section 2 of Appendix B then there should be no problem in obtaining results.

APPENDIX B: FILES AND PROGRAMS

1. SAMPLE EXEC FILE
2. SAMPLE INPUT DATA FILE
3. DRG FORTRAN PROGRAM
4. JIMC FORTRAN PROGRAM
5. SAMPLE OUTPUT FROM DRG FORTRAN A1

1. SAMPLE EXEC FILE

```
&TRACE OFF
*****************************************************************************
&FN = DRG
&FN1 = RELIAB
&TYPE Do you need to compile your program ? (Y)
&READ VAR &R_COMPILE
&IF &R_COMPILE NE Y &GOTO -RUN
-H FORTVS &FN
&IF &RC EQ 0 &GOTO -RUN
&TYPE Your program did not compile; check for errors.
&TYPE Do you wish to view the program LISTING file? (Y)
&READ VAR &RSP1
&IF &RSP1 EQ Y BROWSE &FN LISTING A
&TYPE Do you wish to XEDIT the program file? (Y)
&READ VAR &RESP1
&IF &RESP1 NE Y &EXIT 1
&COMMAND XEDIT &FN FORTRAN A
&TYPE Do you wish to run the program again? (Y)
&READ VAR &RESP2
&IF &RESP2 EQ Y &GOTO -H
&EXIT 1
-RUN
FILEDEF 10 DISK INPUT1 DATA A1
FILEDEF 82 DISK A1 NUM A1
FILEDEF 84 DISK A9 NUM A1
FILEDEF 30 DISK JRELIAB LISTING A1 (LRECL 133
FILEDEF 35 DISK PRELIAB LISTING A1 (LRECL 133
FILEDEF 20 DISK JTHESIS OUT A1
FILEDEF 25 DISK PTHESIS OUT A1
FILEDEF 81 DISK PMATRIXA LISTING (LRECL 133
FILEDEF 83 DISK JMATRIXA LISTING (LRECL 133
FILEDEF 87 DISK PREGMAT DATA A1
FILEDEF 88 DISK JREGMAT DATA A1
FILEDEF 90 DISK YSTAR LISTING (LRECL 133
FILEDEF 89 DISK TRIALS DATA A1
FILEDEF 40 DISK EST OUT A1
FILEDEF 50 DISK JMLEWD OUT A1
FILEDEF 55 DISK PMLEWD OUT A1
FILEDEF 60 DISK JMLESP OUT A1
FILEDEF 65 DISK PMLESP OUT A1
FILEDEF 70 DISK JREGEST OUT A1
FILEDEF 75 DISK PREGEST OUT A1
FILEDEF 15 DISK PWRES1 OUT A1
FILEDEF 39 DISK PWRES2 OUT A1
FILEDEF 49 DISK PWRES3 OUT A1
FILEDEF 16 DISK JWRES1 OUT A1
FILEDEF 38 DISK JWRES2 OUT A1
FILEDEF 48 DISK JWRES3 OUT A1
FILEDEF 52 DISK MLEWD1 NUM A1
FILEDEF 51 DISK MLEWD1 SDV A1
FILEDEF 54 DISK MLEWD9 NUM A1
```

```
FILEDEF 53 DISK MLEWD9 SDV A1
FILEDEF 72 DISK REG8 NUM A1
FILEDEF 71 DISK REG8 SDV A1
FILEDEF 74 DISK REG16 NUM A1
FILEDEF 73 DISK REG16 SDV A1
FILEDEF 77 DISK M1P1 NUM A1
FILEDEF 76 DISK M1P1 SDV A1
FILEDEF 79 DISK M2P1 NUM A1
FILEDEF 78 DISK M2P1 SDV A1
FILEDEF 92 DISK M3P1 NUM A1
FILEDEF 91 DISK M3P1 SDV A1
FILEDEF 18 DISK M1P9 NUM A1
FILEDEF 17 DISK M1P9 SDV A1
FILEDEF 94 DISK M2P9 NUM A1
FILEDEF 93 DISK M2P9 SDV A1
FILEDEF 96 DISK M3P9 NUM A1
FILEDEF 95 DISK M3P9 SDV A1
FILEDEF 62 DISK MLESP1 NUM A1
FILEDEF 61 DISK MLESP1 SDV A1
FILEDEF 64 DISK MLESP9 NUM A1
FILEDEF 63 DISK MLESP9 SDV A1
FILEDEF 06 TERMINAL
LOAD &FN (START
&IF &RC EQ 0 &SKIP 9
&TYPE Your program did not run correctly; check for errors.
&TYPE Do you wish to XEDIT the program file? (Y)
&READ VAR &RESP3
&IF &RESP3 NE Y &EXIT 2
&COMMAND XEDIT &FN FORTRAN A
&TYPE Do you wish to run the program again? (Y)
&READ VAR &RESP4
&IF &RESP4 EQ Y &GOTO -H
&EXIT 2
&TYPE YOUR OUTPUT IS IN THE FILE &FN1 LISTING A
&TYPE Do you wish  to BROWSE your output? (Y)
&READ VAR &RESP
&IF &RESP EQ Y &COMMAND BROWSE &FN1 LISTING A
&TYPE Print your output file?  (Y)
&READ VAR &RESP7
&IF &RESP7 EQ Y &COMMAND PRINT &FN LISTING A
-REDO
&TYPE Do you wish to XEDIT the program file? (Y/N)
&READ VAR &RESP5
&IF &RESP5 EQ Y XEDIT &FN FORTRAN A
&TYPE Do you wish to run the program again? (Y)
&READ VAR &RESP6
&RESP56 = &CONCAT OF &RESP5 &RESP6
&IF &RESP56 EQ YY &GOTO -H
&IF &RESP6 EQ Y &GOTO -RUN
&EXIT
```

2. SAMPLE INPUT DATA FILE

```
5              NUMBER OF FAILURE CAUSES
10             NUMBER OF PHASES ( NPHASE )
1              FIXED RELIABILITY OPTION ( 1: YES ; 0: NO )
1              NUMBER OF FAILURES IN PHASE 1
1              NUMBER OF FAILURES IN PHASE 2
1              NUMBER OF FAILURES IN PHASE 3
1              NUMBER OF FAILURES IN PHASE 4
1              NUMBER OF FAILURES IN PHASE 5
1              NUMBER OF FAILURES IN PHASE 6
1              NUMBER OF FAILURES IN PHASE 7
1              NUMBER OF FAILURES IN PHASE 8
1              NUMBER OF FAILURES IN PHASE 9
1              NUMBER OF FAILURES IN PHASE 10
0.85            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 1
0.86            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 2
0.90            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 3
0.91            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 4
0.93            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 5
0.95            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 6
0.97            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 7
0.99            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 8
0.99            PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 9
0.998           PROB. OF SUCCESS FROM CAUSE 1 IN PHASE 10
0.84            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 1
0.85            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 2
0.87            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 3
0.90            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 4
0.92            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 5
0.95            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 6
0.97            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 7
0.99            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 8
0.99            PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 9
0.998           PROB. OF SUCCESS FROM CAUSE 2 IN PHASE 10
0.83            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 1
0.84            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 2
0.86            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 3
0.88            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 4
0.90            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 5
0.93            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 6
0.96            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 7
0.98            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 8
0.99            PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 9
0.998           PROB. OF SUCCESS FROM CAUSE 3 IN PHASE 10
0.83            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 1
0.84            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 2
0.85            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 3
0.87            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 4
0.89            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 5
0.92            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 6
0.94            PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 7
0.975           PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 8
```

```
0.99           PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 9
0.998          PROB. OF SUCCESS FROM CAUSE 4 IN PHASE 10
0.81           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 1
0.83           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 2
0.84           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 3
0.86           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 4
0.89           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 5
0.91           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 6
0.94           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 7
0.961          PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 8
0.99           PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 9
0.998          PROB. OF SUCCESS FROM CAUSE 5 IN PHASE 10
1             NUMBER OF TRIALS AFTER FAILURE BEFORE A DISCOUNT IS APPLIED
0.0           FRACTION EACH FAILURE IS DISCOUNTED
624712.0      RANDOM NUMBER SEED FOR GGUBFS UNIFORM (0,1) GENERATOR
0.75           FRACTION RELIABILITY IMPROVES AFTER FAILING IN A PHASE
500           NUMBER OF DESIRED REPETITIONS FOR THE SIMULATION
0             INTERMEDIATE INPUT OPTION(1: INT. OUT; 0: NO INT. OUTPUT)
0             SAVE ALL MLE W/ DISCOUNTING ESTIMATES (1: YES; 0: NO )
0             SAVE ALL MLE SINGLE PHASE ESTIMATES (1: YES; 0: NO )
0             SAVE ALL UNWT'D REGRESSION ESTIMATES (1: YES; 0: NO )
0             SAVE ALL METHOD 1 WT'D REG. ESTIMATES (1: YES; 0: NO )
0             SAVE ALL METHOD 2 WT'D REG. ESTIMATES (1: YES; 0: NO )
0             SAVE ALL METHOD 3 WT'D REG. ESTIMATES (1: YES; 0: NO )
1             DISCOUNTING OPTION (1: STRAIGHT % ; 2: LLOYD METHOD)
0.9            PERCENT C.I. FOR C.L. DISCOUNTING METHOD(MUST HAVE A VALUE
1             C.L. DISCOUNT INTERVAL
0.03           WEIGHT FOR PHASE 1
0.03           WEIGHT FOR PHASE 2
0.03           WEIGHT FOR PHASE 1
0.03           WEIGHT FOR PHASE 2
0.03           WEIGHT FOR PHASE 1
0.15           WEIGHT FOR PHASE 2
0.15           WEIGHT FOR PHASE 1
0.15           WEIGHT FOR PHASE 8
0.2            WEIGHT FOR PHASE 9
0.2            WEIGHT FOR PHASE 10
```

3. DRG FORTRAN PROGRAM

```
************************************************************************
*                                                                      *
*          DISCRETE RELIABILITY GROWTH SIMULATION                      *
*                                                                      *
*              PROGRAMMED BY : JAMES E. DRAKE,                         *
*                              JAMES D. CHANDLER,                      *
*                        AND   PAM A. MARKIEWICZ                       *
*                                                                      *
*               LAST MODIFIED 11 JUN 1988                              *
*                                                                      *
*  THE FOLLOWING EXTERNAL FILES ARE USED BY THE PROGRAM                *
*  INPUT  : DATA AND PARAMETER INPUT FILE (DEVICE # 10)                *
*  THESIS : OUTPUT FILE CONTAINING INTERMEDIATE COMPUTATIONS           *
*           (DEVICE # 25)                                              *
*  RELIAB: OUTPUT FILE CONTAINING FINAL RESULTS OF THE SIMULATION      *
*           (DEVICE # 35)                                              *
*  MLEWD  : OUTPUT FILE CONTAINING MLE ESTIMATES USING DISCOUNTING     *
*           FOR EACH PHASE AND EACH REPLICATION                        *
*           (DEVICE # 55)                                              *
*  MLESP  : OUTPUT FILE CONTAINING MLE ESTIMATE FOR EACH SINGLE PHASE  *
*           AND ALL REPLICATIONS USING NO DISCOUNTING                  *
*           (DEVICE # 65)                                              *
*  REGEST : OUTPUT FILE CONTAINING EACH PHASE ESTIMATE FOR EACH        *
*           REPLICATION OF THE EXPONENTIAL REGRESSION ESTIMATE         *
*           (DEVICE # 75)                                              *
*  WREST1 : OUTPUT FILE CONTAINING EACH PHASE ESTIMATE FOR EACH        *
*           REPLICATION OF THE WEIGHTED EXPONENTIAL REGRESSION         *
*           ESTIMATE USING WEIGHTING METHOD 1  (DEVICE #15)            *
*  WREST2 : SAME AS ABOVE USING WEIGHTING METHOD 2 (DEVICE #39)        *
*  WREST3 : SAME AS ABOVE USING WEIGHTING METHOD 3 (DEVICE #49)        *
*                                                                      *
*  THE FOLLOWING IS A LIST OF KEY ARRAYS USED IN THE SIMULATION        *
*                                                                      *
*  A      : MAIN WORKING ARRAY CONTAINS PROBABILITY OF SUCCESS FOR     *
*           EACH FAILURE CAUSE, NUMBER OF TRIALS UNTIL FAILURE FOR     *
*           EACH FAILURE CAUSE AND THE SYSTEM, CAUSE OF FAILURE,       *
*           PHASE NUMBER, ADJUSTED NUMBER OF TRIALS AND ADJUSTED       *
*           NUMBER OF FAILURES                                         *
*           DIMENSION ( ((2*#CAUSES)+6),#FAILURES )                    *
*  NFAPH  : CONTAINS THE NUMBER OF FAILURES IN EACH PHASE              *
*           DIMENSION (1,#PHASES)                                      *
*  NFCAUS : BINARY ARRAY USED TO DETERMINE IF A FAILURE OCCURRED IN    *
*           A PHASE                                                    *
*           DIMENSION ( 1,#FAILURE CAUSES)                             *
*  NTRIAL : CONTAINS THE NUMBER OF TRIALS SINCE LAST FAILURE OR        *
*           DISCOUNTING FOR EACH FAILURE CAUSE                         *
*           DIMENSION ( 1,#FAILURE CAUSES )                            *
*  TRIALS : CONTAINS THE TOTAL NUMBER OF ADJUSTED TRIALS IN A PHASE    *
*           DIMENSION ( 1, # OF PHASES)                                *
*  PHREST : RECORDS THE PHASE ESTIMATE FOR EACH ESTIMATOR WITHIN A     *
*           SINGLE REPLICATION                                         *
```

```
*            DIMENSION (6,#PHASES)                                        *
*            ROW 1 : MLE WITH DISCOUNTING                                 *
*            ROW 2 : SINGLE PHASE MLE                                     *
*            ROW 3 : WOODS REGRESSION ESTIMATE (UNWEIGHTED)               *
*            ROW 4 : WEIGHTED REGRESSION ESTIMATE (METHOD 1)              *
*            ROW 5 : WEIGHTED REGRESSION ESTIMATE (METHOD 2)              *
*            ROW 6 : WEIGHTED REGRESSION ESTIMATE (METHOD 3)              *
* AREL     : CONTAINS ACTUAL SYSTEM RELIABILITY IN EACH PHASE             *
*            DIMENSION (1,#PHASES)                                        *
* YJK      : CONTAINS YJK VALUES UP TO 1000                               *
*            DIMENSION (1,1000)                                           *
* YSTAR    : CONTAINS THE YK VALUES UP TO 1000                            *
*            DIMENSION (#PHASES,1000)                                     *
* VAR      : CONTAINS THE VARIANCE OF THE ESTIMATE AT EACH PHASE          *
*            DIMENSION (1,#PHASES)                                        *
* SVAR1    : CONTAINS THE RUNNING SUM OF 1/VAR(K) UP TO THE KTH PHASE     *
*            DIMENSION (1,#PHASES)                                        *
* SVAR2    : CONTAINS THE RUNNING SUM OF VAR(K) UP TO THE KTH PHASE       *
*            DIMENSION (1,#PHASES)                                        *
* SUMW     : CONTAINS THE RUNNING SUM OF WEIGHTS UP TO THE KTH PHASE      *
*            DIMENSION (1,#PHASES)                                        *
* W        : CONTAINS THE WEIGHT GIVEN TO EACH RELIABILITY ESTIMATE AT    *
*            EACH PHASE. DIMENSION (3,#PHASES)                            *
*            ROW 1: WEIGHT = (1/VAR(K))/(SUM OF 1/VAR(K) UP TO            *
*                                  THE KTH PHASE)                         *
*            ROW 2: WEIGHT = VAR(K)/(SUM OF VAR(K) UP TO KTH PHASE)       *
*            ROW 3: WEIGHT = USER INPUTTED VALUES.                        *
* REG      : ARRAY USED TO COMPUTE THE EXPONENTIAL REGRESSION ESTIMATE    *
*            DIMENSION (5,#PHASES)                                        *
*            ROW 1 : K BAR                                                *
*            ROW 2 : Y BAR                                                *
*            ROW 3 : Y BAR FOR THE PHASE                                  *
*            ROW 4 : B HAT                                                *
*            ROW 5 : A HAT                                                *
* WREG1    : ARRAY USED TO COMPUTE THE WEIGHTED EXPONENTIAL REGRESSION    *
*            ESTIMATE USING METHOD 1 WEIGHTS. DIMENSION (4,#PHASES)       *
*            ROW 1 : X BAR(W) ...(A.K.A. K-BAR(W))                        *
*            ROW 2 : B HAT(W)                                             *
*            ROW 3 : A HAT(W)                                             *
*            ROW 4 : Y BAR(W)                                             *
*                                                                         *
* WREG2    : SAME AS ABOVE USING METHOD 2 WEIGHTS                         *
* WREG3    : SAME AS ABOVE USING METHOD 3 WEIGHTS                         *
* THE REMAINING ARRAYS ARE USED TO COMPUTE THE MEAN AND VARIANCE          *
* OF EACH ESTIMATE AT EACH PHASE. THEY ALL HAVE THE SAME DIMENSIONS       *
* AND STRUCTURE                                                           *
*            DIMENSION (4,#PHASES)                                        *
*            ROW 1 : RUNNING SUM OF ESTIMATES                             *
*            ROW 2 : RUNNING SUM OF SQUARED ESTIMATES                     *
*            ROW 3 : MEAN OF THE ESTIMATES                                *
*            ROW 4 : STANDARD DEVIATION OF THE ESTIMATES                  *
*                                                                         *
* MLEWD    : VALUES FOR THE MLE WITH DISCOUNTING                          *
* MLESP    : VALUES FOR THE SINGLE PHASE MLE                              *
* REGEST   : VALUES FOR THE EXPONENTIAL REGRESSION ESTIMATE               *
* WREST1   : VALUES FOR THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE      *
```

```
*          USING METHOD 1 WEIGHTS.                                        *
*  WREST2 : VALUES FOR THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE      *
*          USING METHOD 2 WEIGHTS.                                        *
*  WREST3 : VALUES FOR THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE      *
*          USING METHOD 3 WEIGHTS.                                        *
*************************************************************************


C  DEFINE AND DIMENSION VARIABLES

      PARAMETER (NR=50,NC=200)
      INTEGER REP,DISOPT,FRELOP,LDI,ALD
      REAL*4 MIN
      REAL*8 DSEED,MLESP,MLEWD,EUL,SUM1,SUMS1,SUM2,SUMS2,SUM3
     C,SUMS3,SUM1A
      DIMENSION NFAPH(NR),A(NR,NC),NFCAUS(NR),NTRIAL(NR),PHREST(6,NR),
     CMLEWD(4,NR),MLESP(4,NR),REGEST(4,NR),AREL(NR),YJK(1000),
     CREG(5,NR),YSTAR(50,1000),TADJTP(1000),VAR(NR),SVAR1(NR),W(3,NR),
     CWREG1(4,NR),WREST1(4,NR),WREST2(4,NR),WREST3(4,NR),
     CSVAR2(NR),WREG2(4,NR),WREG3(4,NR),SUMW(NR)

C  READ IN THE NUMBER OF CAUSES TO BE USED ( NCAUSE ) AND THE NUMBER
C  OF PHASES ( NPHASE ) IN THE TEST

      READ(10,*) NCAUSE
      READ(10,*) NPHASE

C  CHECK IF FIXED RELIABILITY OPTION IS DESIRED. FIX EULER'S NUMBER.

      READ(10,*) FRELOP
      EUL = 0.5772156648

C  CREATE VARIABLES FOR THE ROW INDICES OF THE WORKING MATRIX ( A )
C    IPHASE: PHASE
C    ISYSPR: ACTUAL COMPONENT RELIABILITY
C    INTR: NUMBER OF TRIALS UP TO AND INCLUDING FAILURE
C    IFAILC: CAUSE OF THE FAILURE
C    IADJF: ADJUSTED NUMBER OF FAILURES                                   ED
C           AFTER DISCOUNTING HAS BEEN APPLIED
C    IADJT: ADJUSTED NUMBER OF TRIALS AFTER DISCOUNTING HAS BEEN APPLIED

      IPHASE = (2*NCAUSE)+1
      ISYSPR = IPHASE +1
      INTR = ISYSPR + 1
      IFAILC = INTR + 1
      IADJF = IFAILC + 1
      IADJT = IADJF + 1


C  READ IN THE NUMBER OF FAILURES IN EACH PHASE ( NFAPH(I) ) AND
C  COMPUTE THE TOTAL NUMBER OF FAILURES IN THE TEST ( NFAIL )

      NFAIL = 0
      DO 10 I=1,NPHASE
```

```
          READ(10,*) NFAPH(I)
          NFAIL = NFAIL + NFAPH(I)
 10   CONTINUE


C  INPUT THE PROBABILITY OF SUCCESS IN A SINGLE TRIAL FOR EACH CAUSE
C  IN EACH PHASE IF FRELOP EQUALS ONE.

      IF (FRELOP .EQ. 1) THEN
        DO 15 I=1,NCAUSE
              L = 1
          DO 16 J=1,NPHASE
            READ(10,*) QQ
            DO 17 K= L,L+NFAPH(J)-1
                  A(I,K) = QQ
 17     CONTINUE
              L = L + NFAPH(J)
 16     CONTINUE
 15     CONTINUE
        ELSE

C  INPUT THE PROBABILITY OF SUCCESS IN A SINGLE TRIAL FOR EACH CAUSE
C  IN THE FIRST PHASE IF FRELOP EQUALS ZERO.

      DO 20 I=1,NCAUSE
          READ(10,*) A(I,1)
 20   CONTINUE

      ENDIF

C  INPUT THE REMAINING VARIABLES , THE NUMBER OF SUCCESSFUL TRIALS
C  BEFORE A DISCOUNT IS APPLIED (N); THE DISCOUNT FACTOR (R); THE SEED
C  FOR THE RANDOM NUMBER GENERATOR, GGUBFS, (DSEED); RELIABILITY
C  GROWTH FRACTION (FRIMP); TRIGGER FOR PRINTING INTERMEDIATE OUTPUT
C  (IOPT)
C  TRIGGERS FOR SAVING EACH ESTIMATE AT EACH PHASE FOR EACH ESTIMATOR
C     IOPT1 : MLE WITH DISCOUNTING
C     IOPT2 : SINGLE PHASE MLE
C     IOPT3 : EXPONENTIAL REGRESSION MODEL
C     IOPT4 : WEIGHTED EXPONENTIAL REGRESSION MODEL (METHOD 1)
C     IOPT5 : WEIGHTED EXPONENTIAL REGRESSION MODEL (METHOD 2)
C     IOPT6 : WEIGHTED EXPONENTIAL REGRESSION MODEL (METHOD 3)
C   DISCOUNTING OPTION TRIGGER (DISOPT); LLOYD FAILURE DISCOUNTING
C   PARAMETER (GAMMA); LLOYD DISCOUNT INTERVAL

      READ(10,*) N
      READ(10,*) R
      READ(10,*) DSEED
      READ(10,*) FRIMP
      READ(10,*) NREP
      READ(10,*) IOPT
      READ(10,*) IOPT1
      READ(10,*) IOPT2
      READ(10,*) IOPT3
      READ(10,*) IOPT4
```

```
      READ(10,*) IOPT5
      READ(10,*) IOPT6
      READ(10,*) DISOPT
      READ(10,*) GAMA
      READ(10,*) LDI

C-----READ IN THE USER INPUTTED WEIGHTS FOR COMPUTATION OF METHOD 3.
      DO 25 I=1,NPHASE
           READ(10,*) W(3,I)
 25   CONTINUE

      XNREP = NREP
      DSEED1 = DSEED

C  INITIALIZE THE ARRAYS USED TO COMPUTE THE MEAN AND STANDARD DEVIATION
C  OF EACH ESTIMATOR

      DO 30 J=1,NPHASE
           DO 30 I=1,4
                MLEWD(I,J) = 0.0
                MLESP(I,J) = 0.0
                REGEST(I,J) = 0.0
                WREST1(I,J) = 0.0
                WREST2(I,J) = 0.0
                WREST3(I,J) = 0.0
 30   CONTINUE

      DO 31 J=1,NPHASE
           DO 31 I=1,6
                PHREST(I,J) = 0.0
 31   CONTINUE


      YJK(1) = 0.0
      DO 35 I=1,999
           YJK(I+1) = YJK(I) + 1.0/I
 35   CONTINUE

C  COMPUTE AND STORE THE YSTAR VALUES UP TO 1000
      DO 39 J=1,NPHASE
           YSTAR(J,1) = 1./NFAPH(J)
      DO 41 I = 1,999
           YSTAR(J,I+1)= YSTAR(J,I) + 1.0/(NFAPH(J)+I)
 41   CONTINUE
 39   CONTINUE

C PRINT OUT THE YSTAR MATRIX FOR THE FIRST 219 ENTRIES OF THE 10TH PHASE

      WRITE (90,*) (YSTAR(10,J), J=1,219)


C  COMPUTE AND STORE K BAR FOR THE EXPONENTIAL REGRESSION MODEL

      SUM = 0.0
      DO 50 I=1,NPHASE
```

```
         SUM = SUM + I
         REG(1,I) = SUM/I
 50   CONTINUE

C  MAJOR REPETITION OF THE SIMULATION LOOP

      DO 55  REP=1,NREP

 55   CONTINUE


      DO 500 REP=1,NREP


C  INITIALIZE FAILURE CAUSE VECTOR (NFCAUS)
C  COMPUTE THE INITIAL SYSTEM RELIABILITY

      REL = 1.
      DO 60 I=1,NCAUSE
           NFCAUS(I) = 0
           REL = REL * A(I,1)
 60   CONTINUE

C  INITIALIZE COLUMN (FAILURE # ) COUNTER FOR THE WORKING ARRAY (A)

      J = 1

C  LOOP TO COMPUTE THE NUMBER OF TRIALS UP TO AND INCLUDING FAILURE
C  AND THE CAUSE OF FAILURE FOR EACH FAILURE IN EACH PHASE

      DO 130 K=1,NPHASE

C  SKIP ACTUAL COMPONENT RELIABILITY COMPUTATION AFTER FIRST REP
C  AND FOR FIRST FAILURE

        IF(J.EQ.1) GOTO 75
        IF(REP.GT.1) GOTO 75
        REL = 1.

C  IF FIXED RELIABILITY OPTION IS SELECTED THEN PHASE RELIABILITIES
C  ARE COMPUTED AS FOLLOWS

        IF (FRELOP .EQ. 1) THEN
          DO 65 I=1,NCAUSE
            REL = REL*A(I,J)
            NFCAUS(I) = 0
 65       CONTINUE
        ELSE

C  COMPUTE NEW ACTUAL RELIABILITY FOR THE COMPONENT IN PHASE K

        DO 70 I=1,NCAUSE

C  INCREASE CAUSE PR(SUCCESS) IF IT CAUSED FAILURE IN THE PREVIOUS PHASE
C  COMPUTE NEXT PHASE RELIABILITY AND REINITIALIZE NFCAUS (NOT USED IF
C  FIXED PHASE RELIABILITY OPTION IS SELECTED).
```

```
          IF(NFCAUS(I).EQ.1) THEN
          A(I,J) = A(I,(J-1)) + ((1.  - A(I,(J-1)))*FRIMP)
          ELSEIF(NFCAUS(I).NE.1) THEN
          A(I,J) = A(I,(J-1))
          ELSE
          ENDIF
          REL = REL*A(I,J)
          NFCAUS(I) = 0
 70     CONTINUE

        ENDIF

 75     J1 = 1
        TRTOT = 0.0

C  COMPUTE THE NUMBER OF TRIALS UP TO AND INCLUDING FAILURE AND THE
C  CAUSE OF FAILURE FOR EACH FAILURE IN THE PHASE

        DO 120 L=1,NFAPH(K)
          IF(REP.GT.1) GOTO 90
          IF(J1.EQ.1) GOTO 85
          IF (FRELOP .EQ.  1) GOTO 85
          DO 80 I=1,NCAUSE
            A(I,J) = A(I,(J-1))
 80       CONTINUE
 85       A(ISYSPR,J) = REL
          A(IPHASE,J) = K
 90       MIN = 7.2E75
          DO 110 I=1,NCAUSE

C  ASSIGN # TRIALS FOR CAUSES WITH PR(SUCCESS) = 0 OR 1

            IF(A(I,J).GE.1.) THEN
              A((I+NCAUSE),J) = 7.2E75
              GOTO 100
            ELSEIF(A(I,J).EQ.0.) THEN
              A((I+NCAUSE),J) = 1.
              GOTO 100
            ELSE
            ENDIF

C  CONVERT UNIFORM (0,1) RANDOM VARIABLE TO GEOMETRIC (# TRIALS UNTIL
C  FAILURE ) FOR EACH FAILURE CAUSE. RECORD THE MIN # TRIALS FOR THE
C  CAUSES AS THE SYSTEM # TRIALS UP TO AND INCLUDING FAILURE AND
C  RECORD THE FAILURE CAUSE

            A((I+NCAUSE),J) = INT(1.+(LOG(GGUBFS(DSEED))/LOG(A(I,J))))
 100        IF(A((I+NCAUSE),J).LE.MIN) THEN
              MIN = A((I+NCAUSE),J)
              IMIN = I
            ELSE
            ENDIF
 110      CONTINUE
          A(IFAILC,J) = IMIN
          NFCAUS(IMIN) = 1
```

```
C  COMPUTE THE TOTAL # OF TRIALS FOR THE MLE SINGLE PHASE ESTIMATE AND
C  INCREMENT FAILURE # COUNTERS

          A(INTR,J) = MIN
          TRTOT = TRTOT + A(INTR,J)
          J = J + 1
          J1 = J1 + 1
 120   CONTINUE

C  COMPUTE THE MLE ESTIMATE OF COMPONENT RELIABILITY FOR THIS PHASE AND
C  COMPUTE THE RUNNING SUM OF ESTIMATES AND THE SUM OF ESTIMATES SQUARED
C  FOR COMPUTATION OF THE MEAN AND STANDARD DEVIATION OF THE ESTIMATE

      PHREST(2,K) = (TRTOT - NFAPH(K))/TRTOT
      MLESP(1,K) = MLESP(1,K) + PHREST(2,K)
      MLESP(2,K) = MLESP(2,K) + (PHREST(2,K)**2)

 130   CONTINUE

C  INITIALIZE THE ADJUSTED NUMBER OF FAILURES TO 1 AND THE COUNT OF THE
C  NUMBER OF TRIALS SINCE FAILURE OR DISCOUNTING (NTRIALS(I) ) TO 0
C  IN PREPARATION FOR THE DISCOUNTING ROUTINE

      DO 140 J=1,NFAIL
           A(IADJF,J) = 1.
 140   CONTINUE

      DO 150 I=1,NCAUSE
           NTRIAL(I) = 0
 150   CONTINUE

C  DISCOUNTING ROUTINE REVIEWS ALL PAST FAILURES AND CAUSES TO DATE
C  AND DETERMINES IF THE DISCOUNTING CONDITIONS HAVE BEEN MET. COMPUTES
C  THE ADJUSTED FAILURES, THE ADJUSTED # OF TRIALS AND YJK

C INITIALIZE THE TOTAL ADJUSTED TRIALS IN A PHASE VECTOR, TADJTP;
C INITIALIZE THE SUM OF THE VARIANCES,SVAR,THE VARIANCES,VAR
C AND THE WEIGHTS,W FOR THE WEIGHTED EXPONENTIAL REGRESSION MODEL.
      DO 155 I = 1, NPHASE
               TADJTP(I) = 0
                SVAR1(I) = 0
                SVAR2(I) = 0
                 SUMW(I) = 0
                  VAR(I) = 0
                  W(1,I) = 0
                  W(2,I) = 0
 155   CONTINUE


      SUM1A = 0
      J = 0
      LL = 1
      DO 300 K=1,NPHASE
        DO 200 L=1,NFAPH(K)
          J = J + 1
```

```
C  UPDATES THE NUMBER OF TRIALS SINCE FAILURE OR DISCOUNTING FOR EACH
C  FAILURE CAUSE

           ICAUSE = INT(A(IFAILC,J)+.5)
           DO 160 I=1,NCAUSE
             IF(ICAUSE.EQ.I) THEN
               NTRIAL(I) = 0
             ELSEIF(ICAUSE.NE.I) THEN
               NTRIAL(I) = NTRIAL(I) + INT(A(INTR,J)+.5)
             ELSE
             ENDIF
 160      CONTINUE

 200   CONTINUE

C  CHOOSE DISCOUNTING METHOD TO BE USED

          IF(DISOPT.NE.2) GOTO 180

C  PERFORM LLOYD'S FAILURE DISCOUNTING METHOD

          DO 170 I=1,J
               I1 = INT(A(IFAILC,I)+.5)
               IF(NTRIAL(I1).EQ.0) THEN
                    A(IADJF,I) = 1.0
                    GOTO 170
               ELSE
               ENDIF

C  THIS IS THE MODIFIED LLOYD METHOD USING A DISCOUNT INTERVAL.  THE
C  ORIGINAL DISCOUNT METHOD MAY BE EMPLOYED BY SETTING LDI TO ONE.

          ALD = INT(NTRIAL(I1)/LDI)
          IF(ALD .EQ.  0) THEN
             A(IADJF,I) = 1.0
             GO TO 170
          ELSE
             A(IADJF,I) = 1.0 - ((1.-GAMA)**(1.0/ALD))
          ENDIF

 170      CONTINUE
          GOTO 210

C  PERFORMS STRAIGHT PERCENT FAILURE DISCOUNTING AND
C  COMPUTES THE ADJUSTED # OF FAILURES

 180       DO 190 I=1,J
             I1 = INT(A(IFAILC,I)+.5)
             IF(NTRIAL(I1).EQ.0) THEN
               A(IADJF,I) = 1.
             ELSEIF(NTRIAL(I1).GE.N) THEN
               A(IADJF,I) = A(IADJF,I)*((1.-R)**(NTRIAL(I1)/N))
             ELSE
             ENDIF
 190       CONTINUE
```

```
C  ADJUSTS THE # TRIALS SINCE FAILURE OR DISCOUNTING FOR THOSE CAUSES
C  THAT HAVE MET OR SURPASSED THE DISCOUNTING THRESHOLD
C  FOR THE STRAIGHT PERCENT DISCOUNTING METHOD

         DO 205 I=1,NCAUSE
           IF(NTRIAL(I).GE.N) NTRIAL(I) = MOD(NTRIAL(I),N)
 205     CONTINUE
 210    TADJT = 0.0

C  COMPUTES THE ADJUSTED # OF TRIALS FROM THE ADJUSTED # OF FAILURES
C  AND COMPUTES THE SUM OF THE ADJUSTED # OF TRIALS FOR ESTIMATE COMP.

C  IF ADJUSTED FAILURES ARE APPROACHING 0 THEN ADJUSTED TRIALS MUST
C  BE PRE-SET.

        DO 240 I = 1,J

         IF(A(IADJF,I) .LE. .0000001) THEN
           A(IADJF,I) = .0000001
          ENDIF

         A(IADJT,I) = A(INTR,I)/A(IADJF,I)
         TADJT = TADJT + A(IADJT,I)
 240     CONTINUE


C COMPUTE THE ADJUSTED NUMBER OF TRIALS IN A PHASE

       DO 245 M = LL,(LL+NFAPH(K) - 1)
             TADJTP(K) = TADJTP(K) + A(IADJT,M)
 245   CONTINUE
       LL = LL + NFAPH(K)


C  COMPUTE THE MLE ESTIMATE OF PHASE RELIABILITY USING DISCOUNTING

        PHREST(1,K) = (TADJT - J)/TADJT

C  COMPUTE Y-BAR AND Y-BAR FOR THE PHASE USING THE YSTAR MATRIX IF
C  THE ADJUSTED NUMBER OF TRIALS IS LESS THAN OR EQUAL TO 1000
C  AND USING EULER'S APPROXIMATION IF THE VALUE IS GREATER THAN 1000.

      IF ( NINT(TADJTP(K)) .EQ.  NFAPH(K) )THEN
           REG(3,K) = 0.0
      ELSE IF (NINT(TADJTP(K) - NFAPH(K) ) .LE. 1000 ) THEN
           REG(3,K) = YSTAR(K, NINT(TADJTP(K) -NFAPH(K) ) )
      ELSE
      IX = NINT(TADJTP(K)-1 )
       X = IX
      Q = 12*X
      T = X +1
      S = X+2
      U = (EUL + (LOG(X)) + (1/(2*X)) - (1/(Q*T)) -(1/(Q*T*S)) )
      REG(3,K) = U - YJK(NFAPH(K)-1)
      END IF
```

```
      SUM1A = SUM1A + REG(3,K)
      REG(2,K) = SUM1A/K

C   COMPUTE THE EXPONENTIAL REGRESSION ESTIMATE BEGINNING WITH B HAT

         SUM = 0.0
         SUMS = 0.0
         IF (K.EQ.1) GOTO 252
         DO 250 I = 1,K
              SUM = SUM + ((I-REG(1,K))*REG(3,I))
              SUMS = SUMS + ((I-REG(1,K))**2)
 250     CONTINUE

         REG(4,K) = SUM/SUMS

C   COMPUTE A HAT

         REG(5,K) = REG(2,K) - (REG(4,K)*REG(1,K))

C   COMPUTE AND STORE THE EXPONENTIAL REGRESSION ESTIMATE

         PHREST(3,K) = 1.0 - EXP(-(REG(5,K) + (REG(4,K)*K)))
         IF(PHREST(3,K).LT.0.0) PHREST(3,K)=0.0
         GOTO 255
 252     PHREST(3,K) = 1.0 - EXP(-REG(3,1))
         IF(PHREST(3,K).LT.0.0) PHREST(3,K)=0.0


C   STORE THE RUNNING SUM OF THE ESTIMATES FOR THE CURRENT PHASE AND THE
C   RUNNING SUM OF THE ESTIMATES SQUARED FOR COMPUTATION OF THE MEAN AND
C   STANDARD DEVIATION OF EACH ESTIMATE FOR EACH RELIABILITY GROWTH
C   MODEL

 255    MLEWD(1,K) = MLEWD(1,K) + PHREST(2,K)
        MLEWD(2,K) = MLEWD(2,K) + (PHREST(2,K)**2)
        REGEST(1,K) = REGEST(1,K) + PHREST(3,K)
        REGEST(2,K) = REGEST(2,K) + (PHREST(3,K)**2)

C   COMPUTE THE VARIANCES OF THE UNWEIGHTED EXPONENTIAL REGRESSION
C   ESTIMATES AND STORE THE RUNNING SUM OF THE VARIANCES FOR USE IN THE
C   WEIGHTED REGRESSION MODEL.

      VAR(K)  = (NFAPH(K)*PHREST(1,K))/((1.-PHREST(1,K))**2)
      IF ( VAR(K) .LT. .0000001)THEN
      VAR(K) = .0000001
      END IF
      IF (K .EQ. 1) GO TO 258
      SVAR1(K) = SVAR1(K-1) + (1./VAR(K))
      SVAR2(K) = SVAR2(K-1) + VAR(K)
      SUMW(K) = SUMW(K-1) + W(3,K)
      GO TO 259
 258  SVAR1(K) = (1./VAR(1))
      SVAR2(K) = VAR(1)
      SUMW(K)  = W(3,1)
```

```
C  COMPUTE THE WEIGHTS FOR EACH PHASE
 259  W(1,K) = (1./VAR(K))/SVAR1(K)
      W(2,K) = VAR(K)/SVAR2(K)
C  COMPUTE AND STORE X-BAR(W) AND Y-BAR(W)
      SUMX1 = 0
      SUMY1 = 0
      SUMX2 = 0
      SUMY2 = 0
      SUMX3 = 0
      SUMY3 = 0
      DO 261 I = 1,K
         SUMX1 = SUMX1 + (1./VAR(K))*I
         SUMY1 = SUMY1 + (1./VAR(K))*REG(3,I)
         SUMX2 = SUMX2 + VAR(K)*I
         SUMY2 = SUMY2 + VAR(K)*REG(3,I)
         SUMX3 = SUMX3 + W(3,K)*I
         SUMY3 = SUMY3 + W(3,K)*REG(3,I)


 261  CONTINUE
      WREG1(1,K) = SUMX1/SVAR1(K)
      WREG1(4,K) = SUMY1/SVAR1(K)
      WREG2(1,K) = SUMX2/SVAR2(K)
      WREG2(4,K) = SUMY2/SVAR2(K)
      WREG3(1,K) = SUMX3/SUMW(K)
      WREG3(4,K) = SUMY3/SUMW(K)

C  COMPUTE AND STORE B-HAT(W)

      SUM1  = 0.0
      SUMS1 = 0.0
      SUM2  = 0.0
      SUMS2 = 0.0
      SUM3  = 0.0
      SUMS3 = 0.0
      IF (K .EQ. 1) GO TO 272

      DO 271 I = 1,K
         SUM1  = SUM1 + (W(1,K)*(I-WREG1(1,K))*REG(3,I))
         SUMS1 = SUMS1 + ( W(1,K)*((I-WREG1(1,K))**2))
         SUM2  = SUM2 + (W(2,K)*(I-WREG2(1,K))*REG(3,I))
         SUMS2 = SUMS2 + ( W(2,K)*((I-WREG2(1,K))**2))
         SUM3  = SUM3 + (W(3,K)*(I-WREG3(1,K))*REG(3,I))
         SUMS3 = SUMS3 + ( W(3,K)*((I-WREG3(1,K))**2))
 271  CONTINUE


      WREG1(2,K) = SUM1/SUMS1
      WREG2(2,K) = SUM2/SUMS2
      WREG3(2,K) = SUM3/SUMS3

C COMPUTE AND STORE  A-HAT(W)

      WREG1(3,K) = WREG1(4,K) - (WREG1(2,K)*WREG1(1,K))
      WREG2(3,K) = WREG2(4,K) - (WREG2(2,K)*WREG2(1,K))
```

```
      WREG3(3,K) = WREG3(4,K) - (WREG3(2,K)*WREG3(1,K))

C  COMPUTE AND STORE THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE

      PHREST(4,K) = 1.0 - EXP(-(WREG1(3,K)+(WREG1(2,K)*K)))
      PHREST(5,K) = 1.0 - EXP(-(WREG2(3,K)+(WREG2(2,K)*K)))
      PHREST(6,K) = 1.0 - EXP(-(WREG3(3,K)+(WREG3(2,K)*K)))

      IF (PHREST(4,K) .LT. 0.0) PHREST(4,K) = 0.0
      IF (PHREST(5,K) .LT. 0.0) PHREST(5,K) = 0.0
      IF (PHREST(6,K) .LT. 0.0) PHREST(6,K) = 0.0
      GO TO 275

 272  PHREST(4,K) = 1.0 - EXP(-WREG1(4,1))
      IF (PHREST(4,K) .LT. 0.0) PHREST(4,K) = 0.0

      PHREST(5,K) = 1.0 - EXP(-WREG2(4,1))
      IF (PHREST(5,K) .LT. 0.0) PHREST(5,K) = 0.0

      PHREST(6,K) = 1.0 - EXP(-WREG3(4,1))
      IF (PHREST(6,K) .LT. 0.0) PHREST(6,K) = 0.0

C STORE THE RUNNING SUM OF THE WEIGHTED ESTIMATES FOR THE CURRENT
C PHASE AND THE RUNNING SUM OF THE ESTIMATES SQUARED FOR COMPUTATION OF
C THE MEAN AND STANDARD DEVIATION OF EACH WEIGHTED ESTIMATE FOR THE
C WEIGHTED EXPONENTIAL REGRESSION MODEL.

 275  WREST1(1,K) = WREST1(1,K) + PHREST(4,K)
      WREST1(2,K) = WREST1(2,K) + (PHREST(4,K)**2)

      WREST2(1,K) = WREST2(1,K) + PHREST(5,K)
      WREST2(2,K) = WREST2(2,K) + (PHREST(5,K)**2)

      WREST3(1,K) = WREST3(1,K) + PHREST(6,K)
      WREST3(2,K) = WREST3(2,K) + (PHREST(6,K)**2)

C  STORE THE ACTUAL PHASE RELIABILITY

        AREL(K) = A(ISYSPR,J)

C  PRINT INTERMEDIATE OUTPUT IF REQUESTED AND THE NUMBER OF REPETITIONS
C  IS NOT GREATER THAN 5

        IF(IOPT.NE.1) GOTO 300
        IF(REP.GT.5) GOTO 300

      WRITE(25,1000) REP,K
 1000 FORMAT(T16,'REPETITION NUMBER: ',I4,'    PHASE NUMBER: ',I4)
      WRITE(25,1010) A(ISYSPR,J)
 1010 FORMAT(22X,'ACTUAL COMPONENT RELIABILITY: ',F7.5)
      WRITE(25,1022) PHREST(1,K)
 1022 FORMAT(20X,'MLE ESTIMATE USING DISCOUNTING: ',F7.5)
      WRITE(25,1025) PHREST(2,K)
 1025 FORMAT(18X,'MLE ESTIMATE OF PHASE RELIABILITY: ',F7.5)
      WRITE(25,1027) PHREST(4,K)
 1027 FORMAT(14X,'WEIGHTED REG. ESTIMATE ( METHOD 1 )   : ',F7.5)
```

```
      WRITE(25,1026) PHREST(5,K)
1026 FORMAT(14X,'WEIGHTED REG. ESTIMATE ( METHOD 2 )    : ',F7.5)
      WRITE(25,1029) PHREST(6,K)
1029 FORMAT(14X,'WEIGHTED REG. ESTIMATE ( METHOD 3 )    : ',F7.5)
      WRITE(25,1028) PHREST(3,K)
1028 FORMAT(14X,'REGRESSION ESTIMATE OF PHASE RELIABILITY: ',F7.5)
      WRITE(25,1030)
1030 FORMAT(' ','     ')
      DO 260 I=1,NCAUSE
        WRITE(25,1035)I,A(I,J),A((I+NCAUSE),J)
1035    FORMAT(12X,'CAUSE: ',I3,'    PR(SUCCESS): ',F7.6,'    # TRIALS: ',
     CF10.0)
260   CONTINUE
      WRITE(25,1036)
1036 FORMAT(' ','     ')
      WRITE(25,1040)
1040 FORMAT(4X,'FAIL #',3X,'FAIL CAUSE',3X,'# TRIALS',3X,'ADJ # FAIL',3
     CX,'ADJ # TRIALS')
      DO 270 I=1,J
      WRITE(25,1050)I,A(IFAILC,I),A(INTR,I),A(IADJF,I),A(IADJT,I)
1050 FORMAT(4X,I3,8X,F3.0,7X,F8.0,4X,F8.6,4X,F12.0,3X,F11.4)
270   CONTINUE
      WRITE(25,1060)
1060 FORMAT(' ',///)

300   CONTINUE


C  PRINT EACH OF THE ESTIMATES TO THEIR APPROPRIATE OUTPUT FILE
C  IF REQUESTED

401   IF(IOPT1.NE.1) GOTO 402
      WRITE(55,2000) (PHREST(1,I), I=1,NPHASE)
402   IF(IOPT2.NE.1) GOTO 403
      WRITE(65,2000) (PHREST(2,I), I=1,NPHASE)
403   IF(IOPT3.NE.1) GOTO 404
      WRITE(75,2000) (PHREST(3,I), I=1,NPHASE)
404   IF(IOPT4.NE.1) GOTO 405
      WRITE(15,2000) (PHREST(4,I), I=1,NPHASE)
405   IF(IOPT5.NE.1) GOTO 406
      WRITE(39,2000) (PHREST(5,I), I=1,NPHASE)
406   IF(IOPT4.NE.1) GOTO 500
      WRITE(49,2000) (PHREST(6,I), I=1,NPHASE)
2000 FORMAT(' ',30(F7.6:1X))

500   CONTINUE

C PRINT OUT THE WORKING "A" MATRIX IN MATRIX LISTING A1
        DO 4050 J = 1,(2*NCAUSE)+6
        WRITE(81,*) (A(J,I),I = 1,NFAIL)
4050    CONTINUE

C  PRINT OUT THE THE TOTAL NUMBER OF TRIALS TO SYSTEM FAILURE IN EACH
C  PHASE
        DO 4051 J = 1,NPHASE
           WRITE(89,*) 'T ',TADJTP(J)
```

```
 4051 CONTINUE

C  PRINT OUT THE WEIGHTS COMPUTED BY METHOD 1 TO THE TRIALS FILE
       DO 4052 J = 1,NPHASE
          WRITE(89,*) 'M1 ',W(1,J)
 4052 CONTINUE

C  PRINT OUT THE WEIGHTS COMPUTED BY METHOD 2 TO THE TRIALS FILE
       DO 4053 J = 1,NPHASE
          WRITE(89,*) 'M2 ',W(2,J)
 4053 CONTINUE

C PRINT OUT THE REGRESSION PARAMETERS IN MATRIX FORM TO THE REGMAT FILE

       DO 4054 J = 1,5
          WRITE(87,*) (REG(J,I),I = 1,NPHASE)
 4054  CONTINUE

C PRINT OUT THE WEIGHTED REGRESSION PARAMETERS IN MATRIX FORM TO THE
C REGMAT FILE
       DO 4055 J = 1,4
          WRITE(87,*) (WREG1(J,I),I = 1,NPHASE)
 4055  CONTINUE

       DO 4056 J = 1,4
          WRITE(87,*) (WREG2(J,I),I = 1,NPHASE)
 4056  CONTINUE

       DO 4057 J = 1,4
          WRITE(87,*) (WREG3(J,I),I = 1,NPHASE)
 4057  CONTINUE

C  UPON COMPLETION OF ALL REPETITIONS, COMPUTE THE MEAN AND STANDARD
C  DEVIATION OF EACH ESTIMATE FOR EACH PHASE SKIPPING COMPUTATIONS IF
C  ONLY ONE REPETITION IS REQUIRED

      IF (NREP.LE.1) GOTO 601

      DO 600 I=1,NPHASE
      MLEWD(3,I) = MLEWD(1,I)/XNREP
      MLESP(3,I) = MLESP(1,I)/XNREP
      REGEST(3,I) = REGEST(1,I)/XNREP
      WREST1(3,I) = WREST1(1,I)/XNREP
      WREST2(3,I) = WREST2(1,I)/XNREP
      WREST3(3,I) = WREST3(1,I)/XNREP
      MLEWD(4,I) = SQRT((MLEWD(2,I)-(XNREP*(MLEWD(3,I)**2)))/(XNREP-1))
      MLESP(4,I) = SQRT((MLESP(2,I)-(XNREP*(MLESP(3,I)**2)))/(XNREP-1))
      REGEST(4,I)=SQRT((REGEST(2,I)-(XNREP*(REGEST(3,I)**2)))/(XNREP-1))
      WREST1(4,I)=SQRT((WREST1(2,I)-(XNREP*(WREST1(3,I)**2)))/(XNREP-1))
      WREST2(4,I)=SQRT((WREST2(2,I)-(XNREP*(WREST2(3,I)**2)))/(XNREP-1))
      WREST3(4,I)=SQRT((WREST3(2,I)-(XNREP*(WREST3(3,I)**2)))/(XNREP-1))
 600  CONTINUE

C  PRINT THE FINAL OUTPUT TABLE TO A FILE

 601  WRITE(35,3000)
```

```
3000 FORMAT('0',T47,'DISCRETE RELIABILITY GROWTH SIMULATION')
     WRITE(35,3010)
3010 FORMAT('-',T54,'MODEL PARAMETER SUMMARY')
     WRITE(35,3020) NCAUSE
3020 FORMAT('0',T47,'NUMBER OF POSSIBLE FAILURE CAUSES ',I4)
     IF (FRELOP .EQ. 1) GOTO 4000
     WRITE(35,3030)
3030 FORMAT('0',T38,'CAUSE NUMBER',T64,'SINGLE TRIAL PR( SUCCESS ) FOR
    CPHASE 1')
     DO 3050 M=1,NCAUSE
     WRITE(35,3040) M,A(M,1)
3040 FORMAT(' ',T43,I2,T79,F8.6)
3050 CONTINUE
     WRITE(35,3060) FRIMP
3060 FORMAT('0',T37,'FRACTION CAUSE RELIABILITY IMPROVES AFTER FAILURE
    C',F8.6)
5000 WRITE(35,3080) NPHASE
3080 FORMAT('-',T48,'NUMBER OF PHASES IN THE SIMULATION ',I2)
     WRITE(35,3090)
3090 FORMAT('0',T42,'PHASE NUMBER',T59,'NUMBER OF FAILURES IN THE FIRST
    C PHASE')
     DO 3110 M=1,NPHASE
     WRITE(35,3100) M,NFAPH(M)
3100 FORMAT(' ',T43,I2,T73,I2)
3110 CONTINUE
     WRITE(35,3120) NFAIL
3120 FORMAT('0',T51,'TOTAL NUMBER OF FAILURES ',I4)
     IF(DISOPT.EQ.2) GO TO 3160
     WRITE(35,3130)
3130 FORMAT('-',T38,'DISCOUNTING PERFORMED USING THE CONSTANT FRACTION
    CMETHOD')
     WRITE(35,3140) R
3140 FORMAT('0',T44,'FRACTION EACH FAILURE IS DISCOUNTED ',F8.6)
     WRITE(35,3150) N
3150 FORMAT(' ',T33,'NUMBER OF TRIALS AFTER A FAILURE BEFORE A DISCOUNT
    C IS APPLIED ',I4)
     GO TO 3190
3160 WRITE(35,3170)
3170 FORMAT('-',T44,'DISCOUNTING PERFORMED USING THE LLOYD METHOD')
     WRITE(35,3180) GAMA
3180 FORMAT('0',T39,'PERCENT C.I. ( USED AS DISCOUNT FRACTION ) ',F8.6
    C)
     WRITE(35,3185) LDI
3185 FORMAT('0',T50,'LLOYD DISCOUNT INTERVAL: ',I3)
3190 WRITE(35,3200) DSEED1
3200 FORMAT('-',T46,'RANDOM NUMBER SEED USED ',F15.2)
     WRITE(35,3210) NREP
3210 FORMAT('0',T37,'NUMBER OF REPETITIONS OF THE SIMULATION PERFORMED
    C',I7)
     WRITE(35,3220)
3220 FORMAT('1',T61,'ESTIMATOR:')
     WRITE(35,3230)
3230 FORMAT('0',T48,'SINGLE PHASE MLE WITHOUT DISCOUNTING')
     WRITE(35,3240)
3240 FORMAT('-',T60,'MEAN',T83,'ESTIMATE',T109,'95 %')
     WRITE(35,3250)
```

```
 3250 FORMAT(' ',T12,'PHASE NUMBER',T29,'ACTUAL RELIABILITY',T52,'PREDIC
     CTED RELIABILITY',T78,'STANDARD DEVIATION',T101,'CONFIDENCE INTERVA
     CL')

C  COMPUTE C.I. FOR SINGLE PHASE MLE

      DO 3270 M=1,NPHASE
      CI = (1.96*MLESP(4,M))/SQRT(XNREP)
      CIU = MLESP(3,M) + CI
      CIL = MLESP(3,M) - CI
      WRITE(35,3260) M,AREL(M),MLESP(3,M),MLESP(4,M),CIL,CIU
 3260 FORMAT('0',T17,I2,T34,F8.6,T58,F8.6,T82,F9.6,T99,'( ',F8.6,' , ',F
     C8.6,' )')
 3270 CONTINUE
      WRITE(35,3220)
      WRITE(35,3280)
 3280 FORMAT('0',T42,'MAX LIKELIHOOD ESTIMATE USING DISCOUNTED FAILURES'
     C)
      WRITE(35,3240)
      WRITE(35,3250)

C  COMPUTE C.I. FOR MLE WITH DISCOUNTING

      DO 3290 M=1,NPHASE
      CI = (1.96*MLEWD(4,M))/SQRT(XNREP)
      CIU = MLEWD(3,M) + CI
      CIL = MLEWD(3,M) - CI
      WRITE(35,3260) M,AREL(M),MLEWD(3,M),MLEWD(4,M),CIL,CIU
 3290 CONTINUE

      WRITE(35,3220)
      WRITE(35,3320)
 3320 FORMAT('0',T43,'REGRESSION ESTIMATE USING DISCOUNTED FAILURES')
      WRITE(35,3240)
      WRITE(35,3250)

C  COMPUTE C.I. FOR EXPONENTIAL REGRESSION ESTIMATES

      DO 3330 M=1,NPHASE
      CI = (1.96*REGEST(4,M))/SQRT(XNREP)
      CIU = REGEST(3,M) + CI
      CIL = REGEST(3,M) - CI
      WRITE(35,3260) M,AREL(M),REGEST(3,M),REGEST(4,M),CIL,CIU
 3330 CONTINUE

C-----WEIGHTED REGRESSION   (METHOD 1)
      WRITE(35,3220)
      WRITE(35,3321)
 3321 FORMAT('0',T43,'WEIGHTED REGRESSSION ESTIMATE (METHOD 1 )')

      WRITE(35,3240)
      WRITE(35,3250)

C  COMPUTE C.I. FOR WEIGHTED EXPONENTIAL REGRESSION ESTIMATES

      DO 3331 M=1,NPHASE
```

```
      CI = (1.96*WREST1(4,M))/SQRT(XNREP)
      CIU = WREST1(3,M) + CI
      CIL = WREST1(3,M) - CI
      WRITE(35,3260) M,AREL(M),WREST1(3,M),WREST1(4,M),CIL,CIU
 3331 CONTINUE

C-----WEIGHTED REGRESSION  (METHOD 2)
      WRITE(35,3220)
      WRITE(35,3322)
 3322 FORMAT('0',T43,'WEIGHTED REGRESSION ESTIMATE (METHOD 2) ')

      WRITE(35,3240)
      WRITE(35,3250)

C  COMPUTE C.I. FOR WEIGHTED EXPONENTIAL REGRESSION ESTIMATES

      DO 3332 M=1,NPHASE
      CI = (1.96*WREST2(4,M))/SQRT(XNREP)
      CIU = WREST2(3,M) + CI
      CIL = WREST2(3,M) - CI
      WRITE(35,3260) M,AREL(M),WREST2(3,M),WREST2(4,M),CIL,CIU
 3332 CONTINUE

C-----WEIGHTED REGRESSION  (METHOD 3)
      WRITE(35,3220)
      WRITE(35,3323)
 3323 FORMAT('0',T43,'WEIGHTED REGRESSION ESTIMATE (METHOD 3) ')

      WRITE(35,3240)
      WRITE(35,3250)

C  COMPUTE C.I. FOR WEIGHTED EXPONENTIAL REGRESSION ESTIMATES

      DO 3333 M=1,NPHASE
      CI = (1.96*WREST3(4,M))/SQRT(XNREP)
      CIU = WREST3(3,M) + CI
      CIL = WREST3(3,M) - CI
      WRITE(35,3260) M,AREL(M),WREST3(3,M),WREST3(4,M),CIL,CIU
 3333 CONTINUE

      WRITE(35,3340)
 3340 FORMAT('1',T59,'RECAPITULATION'//)
      WRITE(35,3350)
 3350 FORMAT('-',T3,'PHASE',T11,'ACTUAL',T28,'MEAN',T38,'EST',T53,
     C'MEAN',T63,'EST',T78,'MEAN',T88,'EST',T103,'MEAN',T113,'EST')
      WRITE(35,3360)
 3360 FORMAT(' ',T11,'RELIAB',T28,'WT',T38,'STD',T53,'MLE',T63,'STD',T7
     C7,'PHASE',T88,'STD',T103,'REG',T113,'STD')
      WRITE(35,3370)
 3370 FORMAT(' ',T28,'REG',T35,'DEVIATION',T53,'W/D',T60,'DEVIATION'
     C,T78,'MLE',T85,'DEVIATION',T103,'EST',T110,'DEVIATION')
      WRITE(35,3375)
 3375 FORMAT(' ',T28,'EST'/)
      DO 650 I=1,NPHASE
      WRITE(35,3380) I,AREL(I),WREST1(3,I),WREST1(4,I),MLEWD(3,I)
     C,MLEWD(4,I),MLESP(3,I),MLESP(4,I),REGEST(3,I),REGEST(4,I)
```

```
 3380 FORMAT('0',T4,I3,T11,F7.6,T26,F7.6,T36,F7.6,T51,F7.6,T61,F7.6
     C,T76,F7.6,T86,F7.6,T101,F7.6,T111,F7.6)
 650  CONTINUE

C-----PAGE 2 OF RECAPITULATION:

      WRITE(35,3381)
 3381 FORMAT('1',T59,'RECAPITULATION CONT.'//)

      WRITE(35,3382)
 3382 FORMAT('-',T3,'PHASE',T11,'ACTUAL',T28,'MEAN',T38,'EST',T53,
     C'MEAN',T63,'EST',T78,'MEAN',T88,'EST',T103,'MEAN',T113,'EST')
      WRITE(35,3383)
 3383 FORMAT(' ',T11,'RELIAB',T28,'REG',T38,'STD',T53,'METHOD',T63,
     C'STD',T77,'METHOD',T88,'STD',T103,'METHOD',T113,'STD')
      WRITE(35,3384)
 3384 FORMAT(' ',T28,'EST',T35,'DEVIATION',T53,'ONE',T60,'DEVIATION'
     C,T78,'TWO',T85,'DEVIATION',T103,'THREE',T110,'DEVIATION')
      DO 651 I=1,NPHASE
      WRITE(35,3385) I,AREL(I),REGEST(3,I),REGEST(4,I),WREST1(3,I)
     C,WREST1(4,I),WREST2(3,I),WREST2(4,I),WREST3(3,I),WREST3(4,I)
 3385 FORMAT('0',T4,I3,T11,F7.6,T26,F7.6,T36,F7.6,T51,F7.6,T61,F7.6
     C,T76,F7.6,T86,F7.6,T101,F7.6,T111,F7.6)



C PRINT RELIABILITY ESTIMATES TO FILES FOR PLOTTING PURPOSES

      WRITE(51,3400) MLEWD(4,I)
      WRITE(52,3400) MLEWD(3,I)
      WRITE(61,3400) MLESP(4,I)
      WRITE(62,3400) MLESP(3,I)
      WRITE(71,3400) REGEST(4,I)
      WRITE(72,3400) REGEST(3,I)
      WRITE(76,3400) WREST1(4,I)
      WRITE(77,3400) WREST1(3,I)
      WRITE(78,3400) WREST2(4,I)
      WRITE(79,3400) WREST2(3,I)
      WRITE(91,3400) WREST3(4,I)
      WRITE(92,3400) WREST3(3,I)
      WRITE(82,3400) AREL(I)
 3400 FORMAT(' ',F7.6)

 651  CONTINUE



      GO TO 6000

 4000 WRITE(35,4010)
 4010 FORMAT(1X,//,T50,'FIXED PHASE RELIABILITY OPTION')
```

```
      WRITE(35,4020)
 4020 FORMAT('-',T38,'PHASE NUMBER',T78,'ACTUAL RELIABILITY')
      DO 4030 M=1,NPHASE
        WRITE(35,4040) M,AREL(M)
 4040 FORMAT('0',T41,I2,T83,F8.6)
 4030 CONTINUE
      GO TO 5000
 6000 CONTINUE

      STOP
      END
```

4. JIMC FORTRAN PROGRAM

```
*************************************************************************
*                                                                       *
*          DISCRETE RELIABILITY GROWTH SIMULATION                       *
*                                                                       *
*              PROGRAMMED BY JAMES E DRAKE,                             *
*                            JAMES D CHANDLER,                          *
*                        AND PAM A MARKIEWICZ
*               LAST MODIFIED 11 JUN 1988                               *
*                                                                       *
*  THE FOLLOWING EXTERNAL FILES ARE USED BY THE PROGRAM                 *
*  INPUT  : DATA AND PARAMETER INPUT FILE (DEVICE # 10)                 *
*  THESIS : OUTPUT FILE CONTAINING INTERMEDIATE COMPUTATIONS            *
*           (DEVICE # 20)                                               *
*  RELIAB: OUTPUT FILE CONTAINING FINAL RESULTS OF THE SIMULATION       *
*           (DEVICE # 30)                                               *
*  EST    : OUTPUT FILE CONTAINING EACH PHASE ESTIMATE FOR EACH         *
*          REPLICATION OF THE WOODS WEIGHTED AVERAGE ESTIMATE           *
*          (DEVICE #40)                                                 *
*  MLEWD  : OUTPUT FILE CONTAINING MLE ESTIMATES USING DISCOUNTING      *
*           FOR EACH PHASE AND EACH REPLICATION                         *
*           (DEVICE # 50)                                               *
*  MLESP  : OUTPUT FILE CONTAINING MLE ESTIMATE FOR EACH SINGLE PHASE   *
*           AND ALL REPLICATIONS USING NO DISCOUNTING                   *
*           (DEVICE # 60)                                               *
*  REGEST : OUTPUT FILE CONTAINING EACH PHASE ESTIMATE FOR EACH         *
*           REPLICATION OF THE EXPONENTIAL REGRESSION ESTIMATE          *
*           (DEVICE # 70)                                               *
*                                                                       *
*  THE FOLLOWING IS A LIST OF KEY ARRAYS USED IN THE SIMULATION         *
*                                                                       *
*  A      : MAIN WORKING ARRAY CONTAINS PROBABILITY OF SUCCESS FOR      *
*           EACH FAILURE CAUSE, NUMBER OF TRIALS UNTIL FAILURE FOR      *
*           EACH FAILURE CAUSE AND THE SYSTEM, CAUSE OF FAILURE,        *
*           PHASE NUMBER, ADJUSTED NUMBER OF TRIALS AND ADJUSTED        *
*           NUMBER OF FAILURES                                          *
*           DIMENSION ( ((2*#CAUSES)+6),#FAILURES )                     *
*  NFAPH  : CONTAINS THE NUMBER OF FAILURES IN EACH PHASE               *
*           DIMENSION (1,#PHASES)                                       *
*  NFCAUS : BINARY ARRAY USED TO DETERMINE IF A FAILURE OCCURRED IN     *
*           A PHASE                                                     *
*           DIMENSION ( 1,#FAILURE CAUSES)                              *
*  NTRIAL : CONTAINS THE NUMBER OF TRIALS SINCE LAST FAILURE OR         *
*           DISCOUNTING FOR EACH FAILURE CAUSE                          *
*           DIMENSION ( 1,#FAILURE CAUSES )                             *
*  TADJTP : CONTAINS THE TOTAL NUMBER OF ADJUSTED TRIALS IN A PHASE     *
*           DIMENSION ( 1, # OF PHASES)                                 *
*  PHREST : RECORDS THE PHASE ESTIMATE FOR EACH ESTIMATOR WITHIN A      *
*           SINGLE REPLICATION                                          *
*           DIMENSION (7,#PHASES)                                       *
*           ROW 1 : WOODS WEIGHTED AVERAGE EST                          *
*           ROW 2 : MLE WITH DISCOUNTING                                *
```

```
*            ROW 3 : SINGLE PHASE MLE                                         *
*            ROW 4 : WOODS REGRESSION ESTIMATE (UNWEIGHTED)                   *
*            ROW 5 : WEIGHTED REGRESSION ESTIMATE (METHOD 1)                  *
*            ROW 6 : WEIGHTED REGRESSION ESTIMATE (METHOD 2)                  *
*            ROW 7 : WEIGHTED REGRESSION ESTIMATE (METHOD 3)                  *
*  AREL    : CONTAINS ACTUAL SYSTEM RELIABILITY IN EACH PHASE                 *
*            DIMENSION (1,#PHASES)                                            *
*  CUMSF   : CONTAINS THE NUMBER OF SUCCESS AND FAILURES FOR EACH             *
*            FAILURE CAUSE (USED WITH WOODS WEIGHTED AVERAGE EST.)            *
*            DIMENSION (3,#FAILUE CAUSES)                                     *
*            ROW 1 : NUMBER OF FAILURES                                       *
*            ROW 2 : NUMBER OF SUCCESSES                                      *
*            ROW 3 : ADJUSTED NUMBER OF SUCCESSES                             *
*  YJK     : CONTAINS YJK VALUES UP TO 1000                                   *
*            DIMENSION (1,1000)                                               *
*  VAR     : CONTAINS THE VARIANCE OF THE ESTIMATE AT EACH PHASE              *
*            DIMENSION (1,#PHASES)                                            *
*  SVAR1   : CONTAINS THE RUNNING SUM OF 1/VAR(K) UP TO THE KTH PHASE         *
*            DIMENSION (1,#PHASES)                                            *
*  SVAR2   : CONTAINS THE RUNNING SUM OF VAR(K) UP TO THE KTH PHASE           *
*            DIMENSION (1,#PHASES)                                            *
*  SUMW    : CONTAINS THE RUNNING SUM OF WEIGHTS UP TO THE KTH PHASE          *
*            DIMENSION (1,#PHASES)                                            *
*  W       : CONTAINS THE WEIGHT GIVEN TO EACH RELIABILITY ESTIMATE AT        *
*            EACH PHASE. DIMENSION (3,#PHASES)                                *
*            ROW 1: WEIGHT = (1/VAR(K))/(SUM OF 1/VAR(K) UP TO                *
*                                 THE KTH PHASE)                              *
*            ROW 2: WEIGHT = VAR(K)/(SUM OF VAR(K) UP TO KTH PHASE)           *
*            ROW 3: WEIGHT = USER INPUTTED VALUES.                             *
*  REG     : ARRAY USED TO COMPUTE THE EXPONENTIAL REGRESSION ESTIMATE        *
*            DIMENSION (5,#PHASES)                                            *
*            ROW 1 : K BAR                                                    *
*            ROW 2 : Y BAR                                                    *
*            ROW 3 : Y BAR FOR THE PHASE                                      *
*            ROW 4 : B HAT                                                    *
*            ROW 5 : A HAT                                                    *
*  WREG1   : ARRAY USED TO COMPUTE THE WEIGHTED EXPONENTIAL REGRESSION        *
*            ESTIMATE USING METHOD 1 WEIGHTS. DIMENSION (4,#PHASES)           *
*            ROW 1 : X BAR(W)                                                 *
*            ROW 2 : B HAT(W)                                                 *
*            ROW 3 : A HAT(W)                                                 *
*            ROW 4 : Y BAR(W)                                                 *
*                                                                             *
*  WREG2   : SAME AS ABOVE USING METHOD 2 WEIGHTS                             *
*  WREG3   : SAME AS ABOVE USING METHOD 3 WEIGHTS                             *
*  THE REMAINING ARRAYS ARE USED TO COMPUTE THE MEAN AND VARIANCE             *
*  OF EACH ESTIMATE AT EACH PHASE. THEY ALL HAVE THE SAME DIMENSIONS          *
*  AND STRUCTURE                                                              *
*            DIMENSION (4,#PHASES)                                            *
*            ROW 1 : RUNNING SUM OF ESTIMATES                                 *
*            ROW 2 : RUNNING SUM OF SQUARED ESTIMATES                         *
*            ROW 3 : MEAN OF THE ESTIMATES                                    *
*            ROW 4 : STANDARD DEVIATION OF THE ESTIMATES                      *
*                                                                             *
*  MLEWD   : VALUES FOR THE MLE WITH DISCOUNTING                              *
*  MLESP   : VALUES FOR THE SINGLE PHASE MLE                                  *
```

```
*  REGEST : VALUES FOR THE EXPONENTIAL REGRESSION ESTIMATE               *
*  WREST1 : VALUES FOR THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE      *
*           USING METHOD 1 WEIGHTS.                                       *
*  WREST2 : VALUES FOR THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE      *
*           USING METHOD 2 WEIGHTS.                                       *
*  WREST3 : VALUES FOR THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE      *
*           USING METHOD 3 WEIGHTS.                                       *
**************************************************************************


C  DEFINE AND DIMENSION VARIABLES

      PARAMETER (NR=50,NC=200)
      INTEGER REP,DISOPT,FRELOP,LDI,ALD
      REAL*4 MIN
      REAL*8 DSEED,MLESP,MLEWD,EUL,SUM1,SUMS1,SUM2,SUMS2,SUM3
     C,SUMS3
      DIMENSION NFAPH(NR),A(NR,NC),NFCAUS(NR),NTRIAL(NR),PHREST(7,NR),
     CMLEWD(4,NR),MLESP(4,NR),REGEST(4,NR),AREL(NR),YJK(1000),
     CREG(5,NR),TADJTP(1000),VAR(NR),SVAR1(NR),W(3,NR),
     CWREG1(4,NR),WREST1(4,NR),WREST2(4,NR),WREST3(4,NR),
     CSVAR2(NR),WREG2(4,NR),WREG3(4,NR),SUMW(NR),EST(4,NR),CUMSF(3,NR)

C  READ IN THE NUMBER OF CAUSES TO BE USED ( NCAUSE ) AND THE NUMBER
C  OF PHASES ( NPHASE ) IN THE TEST

      READ(10,*) NCAUSE
      READ(10,*) NPHASE

C  CHECK IF FIXED RELIABILITY OPTION IS DESIRED. FIX EULER'S NUMBER.

      READ(10,*) FRELOP
      EUL = 0.5772156648

C  CREATE VARIABLES FOR THE ROW INDICES OF THE WORKING MATRIX ( A )
C    IPHASE: PHASE
C    ISYSPR: ACTUAL COMPONENT RELIABILITY
C    INTR: NUMBER OF TRIALS UP TO AND INCLUDING FAILURE
C    IFAILC: CAUSE OF THE FAILURE
C    IADJF: ADJUSTED NUMBER OF FAILURES                                ED
C           AFTER DISCOUNTING HAS BEEN APPLIED
C    IADJT: ADJUSTED NUMBER OF TRIALS AFTER DISCOUNTING HAS BEEN APPLIED
C    IYJK: YJK COMPUTED ON THE ADJUSTED NUMBER OF TRIALS

      IPHASE = (2*NCAUSE)+1
      ISYSPR = IPHASE +1
      INTR = ISYSPR + 1
      IFAILC = INTR + 1
      IADJF = IFAILC + 1
      IADJT = IADJF + 1
      IYJK = IADJT + 1
```

```
C  READ IN THE NUMBER OF FAILURES IN EACH PHASE ( NFAPH(I) ) AND
C  COMPUTE THE TOTAL NUMBER OF FAILURES IN THE TEST ( NFAIL )

      NFAIL = 0
      DO 10 I=1,NPHASE
           READ(10,*) NFAPH(I)
           NFAIL = NFAIL + NFAPH(I)
 10   CONTINUE

C  INPUT THE PROBABILITY OF SUCCESS IN A SINGLE TRIAL FOR EACH CAUSE
C  IN EACH PHASE IF FRELOP EQUALS ONE.

      IF (FRELOP .EQ. 1) THEN
        DO 15 I=1,NCAUSE
              L =1
           DO 16 J=1,NPHASE
             READ(10,*) QQ
               DO 17 K = L,L+NFAPH(J)-1
                         A(I,K) = QQ
 17     CONTINUE
                 L = L+NFAPH(J)
 16     CONTINUE
 15     CONTINUE
      ELSE

C  INPUT THE PROBABILITY OF SUCCESS IN A SINGLE TRIAL FOR EACH CAUSE
C  IN THE FIRST PHASE IF FRELOP EQUALS ZERO.

      DO 20 I=1,NCAUSE
           READ(10,*) A(I,1)
 20   CONTINUE

      ENDIF

C  INPUT THE REMAINING VARIABLES , THE NUMBER OF SUCCESSFUL TRIALS
C  BEFORE A DISCOUNT IS APPLIED (N); THE DISCOUNT FACTOR (R); THE SEED
C  FOR THE RANDOM NUMBER GENERATOR, GGUBFS, (DSEED); RELIABILITY
C  GROWTH FRACTION (FRIMP); TRIGGER FOR PRINTING INTERMEDIATE OUTPUT
C  (IOPT)
C  TRIGGERS FOR SAVING EACH ESTIMATE AT EACH PHASE FOR EACH ESTIMATOR
C     IOPT1 : WOODS WEIGHTED AVERAGE MODEL
C     IOPT2 : MLE WITH DISCOUNTING
C     IOPT3 : SINGLE PHASE MLE
C     IOPT4 : EXPONENTIAL REGRESSION MODEL
C     IOPT5 : WEIGHTED EXPONENTIAL REGRESSION MODEL (METHOD 1)
C     IOPT6 : WEIGHTED EXPONENTIAL REGRESSION MODEL (METHOD 2)
C     IOPT7 : WEIGHTED EXPONENTIAL REGRESSION MODEL (METHOD 3)
C   DISCOUNTING OPTION TRIGGER (DISOPT); LLOYD FAILURE DISCOUNTING
C   PARAMETER (GAMMA); LLOYD DISCOUNT INTERVAL

      READ(10,*) N
      READ(10,*) R
      READ(10,*) DSEED
      READ(10,*) FRIMP
      READ(10,*) NREP
      READ(10,*) IOPT
```

```
      READ(10,*) IOPT1
      READ(10,*) IOPT2
      READ(10,*) IOPT3
      READ(10,*) IOPT4
      READ(10,*) IOPT5
      READ(10,*) IOPT6
      READ(10,*) IOPT7
      READ(10,*) DISOPT
      READ(10,*) GAMA
      READ(10,*) LDI

C-----READ IN THE USER INPUTTED WEIGHTS FOR COMPUTATION OF METHOD 3.
      DO 25 I=1,NPHASE
           READ(10,*) W(3,I)
 25   CONTINUE
      XNREP = NREP
      DSEED1 = DSEED

C  INITIALIZE THE ARRAYS USED TO COMPUTE THE MEAN AND STANDARD DEVIATION
C  OF EACH ESTIMATOR

      DO 30 J=1,NPHASE
           DO 30 I=1,4
                EST(I,J) = 0.0
                MLEWD(I,J) = 0.0
                MLESP(I,J) = 0.0
                REGEST(I,J) = 0.0
                WREST1(I,J) = 0.0
                WREST2(I,J) = 0.0
                WREST3(I,J) = 0.0
 30   CONTINUE
      DO 31 J=1,NPHASE
           DO 31 I=1,6
                PHREST(I,J) = 0.0
 31   CONTINUE


C  COMPUTE AND STORE THE YJK VALUES UP TO 1000

      YJK(1) = 0.0
      DO 40 I=1,999
           YJK(I+1) = YJK(I) + 1.0/I
 40   CONTINUE

C  COMPUTE AND STORE K BAR FOR THE EXPONENTIAL REGRESSION MODEL

      SUM = 0.0
      DO 50 I=1,NPHASE
         SUM = SUM + I
         REG(1,I) = SUM/I
 50   CONTINUE

C  MAJOR REPETITION OF THE SIMULATION LOOP
      DO 500 REP=1,NREP
```

```
C  INITIALIZE FAILURE CAUSE VECTOR (NFCAUS) AND (CUMSF)
C  COMPUTE THE INITIAL SYSTEM RELIABILITY

      REL = 1.
      DO 60 I=1,NCAUSE
           NFCAUS(I) = 0
           REL = REL * A(I,1)
           DO 60 J=1,3
              CUMSF(J,I) = 0
 60   CONTINUE

C  INITIALIZE COLUMN (FAILURE # ) COUNTER FOR THE WORKING ARRAY (A)

      J = 1

C  LOOP TO COMPUTE THE NUMBER OF TRIALS UP TO AND INCLUDING FAILURE
C  AND THE CAUSE OF FAILURE FOR EACH FAILURE IN EACH PHASE

      DO 130 K=1,NPHASE

C  SKIP ACTUAL COMPONENT RELIABILITY COMPUTATION AFTER FIRST REP
C  AND FOR FIRST FAILURE

        IF(J.EQ.1) GOTO 75
        IF(REP.GT.1) GOTO 75
        REL = 1.

C  IF FIXED RELIABILITY OPTION IS SELECTED THEN PHASE RELIABILITIES
C  ARE COMPUTED AS FOLLOWS

        IF (FRELOP .EQ. 1) THEN
          DO 65 I=1,NCAUSE
            REL = REL*A(I,J)
            NFCAUS(I) = 0
 65       CONTINUE
        ELSE

C  COMPUTE NEW ACTUAL RELIABILITY FOR THE COMPONENT IN PHASE K

        DO 70 I=1,NCAUSE

C  INCREASE CAUSE PR(SUCCESS) IF IT CAUSED FAILURE IN THE PREVIOUS PHASE
C  COMPUTE NEXT PHASE RELIABILITY AND REINITIALIZE NFCAUS (NOT USED IF
C  FIXED PHASE RELIABILITY OPTION IS SELECTED).

          IF(NFCAUS(I).EQ.1) THEN
          A(I,J) = A(I,(J-1)) + ((1. - A(I,(J-1)))*FRIMP)
          ELSEIF(NFCAUS(I).NE.1) THEN
          A(I,J) = A(I,(J-1))
          ELSE
          ENDIF
          REL = REL*A(I,J)
          NFCAUS(I) = 0
 70     CONTINUE

        ENDIF
```

```
 75     J1 = 1
        TRTOT = 0.0

C  COMPUTE THE NUMBER OF TRIALS UP TO AND INCLUDING FAILURE AND THE
C  CAUSE OF FAILURE FOR EACH FAILURE IN THE PHASE

        DO 120 L=1,NFAPH(K)
          IF(REP.GT.1) GOTO 90
          IF(J1.EQ.1) GOTO 85
          IF (FRELOP .EQ. 1) GOTO 85
          DO 80 I=1,NCAUSE
            A(I,J) = A(I,(J-1))
 80       CONTINUE
 85       A(ISYSPR,J) = REL
          A(IPHASE,J) = K
 90       MIN = 7.2E75
          DO 110 I=1,NCAUSE

C  ASSIGN # TRIALS FOR CAUSES WITH PR(SUCCESS) = 0 OR 1

            IF(A(I,J).GE.1.) THEN
              A((I+NCAUSE),J) = 7.2E75
              GOTO 100
            ELSEIF(A(I,J).EQ.0.) THEN
              A((I+NCAUSE),J) = 1.
              GOTO 100
            ELSE
            ENDIF

C  CONVERT UNIFORM (0,1) RANDOM VARIABLE TO GEOMETRIC (# TRIALS UNTIL
C  FAILURE ) FOR EACH FAILURE CAUSE. RECORD THE MIN # TRIALS FOR THE
C  CAUSES AS THE SYSTEM # TRIALS UP TO AND INCLUDING FAILURE AND
C  RECORD THE FAILURE CAUSE

            A((I+NCAUSE),J) = INT(1.+(LOG(GGUBFS(DSEED))/LOG(A(I,J))))
 100        IF(A((I+NCAUSE),J).LE.MIN) THEN
              MIN = A((I+NCAUSE),J)
              IMIN = I
            ELSE
            ENDIF
 110      CONTINUE
          A(IFAILC,J) = IMIN
          NFCAUS(IMIN) = 1

C  COMPUTE THE TOTAL # OF TRIALS FOR THE MLE SINGLE PHASE ESTIMATE AND
C  INCREMENT FAILURE # COUNTERS

          A(INTR,J) = MIN
          TRTOT = TRTOT + A(INTR,J)
          J = J + 1
          J1 = J1 + 1
 120  CONTINUE
```

```
C  COMPUTE THE MLE ESTIMATE OF COMPONENT RELIABILITY FOR THIS PHASE AND
C  COMPUTE THE RUNNING SUM OF ESTIMATES AND THE SUM OF ESTIMATES SQUARED
C  FOR COMPUTATION OF THE MEAN AND STANDARD DEVIATION OF THE ESTIMATE

      PHREST(3,K) = (TRTOT - NFAPH(K))/TRTOT
      MLESP(1,K) = MLESP(1,K) + PHREST(3,K)
      MLESP(2,K) = MLESP(2,K) + (PHREST(3,K)**2)

 130  CONTINUE

C  INITIALIZE THE ADJUSTED NUMBER OF FAILURES TO 1 AND THE COUNT OF THE
C  NUMBER OF TRIALS SINCE FAILURE OR DISCOUNTING (NTRIALS(I) ) TO 0
C  IN PREPARATION FOR THE DISCOUNTING ROUTINE

      DO 140 J=1,NFAIL
           A(IADJF,J) = 1.
 140  CONTINUE

      DO 150 I=1,NCAUSE
           NTRIAL(I) = 0
 150  CONTINUE

C INITIALIZE THE VARIANCE,VAR,THE SUM OF 1/VAR,SVAR,AND THE WEIGHTS,W.
      DO 155 I=1,NPHASE
                SVAR1(I) = 0
                SVAR2(I) = 0
                 SUMW(I) = 0
                  VAR(I) = 0
                  W(1,I) = 0
                  W(2,I) = 0
 155  CONTINUE

C  DISCOUNTING ROUTINE REVIEWS ALL PAST FAILURES AND CAUSES TO DATE
C  AND DETERMINES IF THE DISCOUNTING CONDITIONS HAVE BEEN MET. COMPUTES
C  THE ADJUSTED FAILURES, THE ADJUSTED # OF TRIALS AND YJK

      J = 0
      DO 300 K=1,NPHASE
        DO 200 L=1,NFAPH(K)
          J = J + 1

C  UPDATES THE NUMBER OF TRIALS SINCE FAILURE OR DISCOUNTING FOR EACH
C  FAILURE CAUSE

          ICAUSE = INT(A(IFAILC,J)+.5)
          DO 160 I=1,NCAUSE
            IF(ICAUSE.EQ.I) THEN
              NTRIAL(I) = 0
            ELSEIF(ICAUSE.NE.I) THEN
              NTRIAL(I) = NTRIAL(I) + INT(A(INTR,J)+.5)
            ELSE
            ENDIF
 160      CONTINUE

 200  CONTINUE
```

```
C   CHOOSE DISCOUNTING METHOD TO BE USED

          IF(DISOPT.NE.2) GOTO 180

C   PERFORM LLOYD'S FAILURE DISCOUNTING METHOD

          DO 170 I=1,J
               I1 = INT(A(IFAILC,I)+.5)
               IF(NTRIAL(I1).EQ.0) THEN
                    A(IADJF,I) = 1.0
                    GOTO 170
               ELSE
               ENDIF

C   THIS IS THE MODIFIED LLOYD METHOD USING A DISCOUNT INTERVAL.  THE
C   ORIGINAL DISCOUNT METHOD MAY BE EMPLOYED BY SETTING LDI TO ONE.

          ALD = INT(NTRIAL(I1)/LDI)
          IF(ALD .EQ.  0) THEN
             A(IADJF,I) = 1.0
             GO TO 170
          ELSE
             A(IADJF,I) = 1.0 - ((1.-GAMA)**(1.0/ALD))
          ENDIF

 170      CONTINUE
          GOTO 210

C   PERFORMS STRAIGHT PERCENT FAILURE DISCOUNTING AND
C   COMPUTES THE ADJUSTED # OF FAILURES

 180       DO 190 I=1,J
             I1 = INT(A(IFAILC,I)+.5)
             IF(NTRIAL(I1).EQ.0) THEN
               A(IADJF,I) = 1.
             ELSEIF(NTRIAL(I1).GE.N) THEN
               A(IADJF,I) = A(IADJF,I)*((1.-R)**(NTRIAL(I1)/N))
             ELSE
             ENDIF
 190       CONTINUE

C   ADJUSTS THE # TRIALS SINCE FAILURE OR DISCOUNTING FOR THOSE CAUSES
C   THAT HAVE MET OR SURPASSED THE DISCOUNTING THRESHOLD
C   FOR THE STRAIGHT PERCENT DISCOUNTING METHOD

           DO 205 I=1,NCAUSE
             IF(NTRIAL(I).GE.N) NTRIAL(I) = MOD(NTRIAL(I),N)
 205       CONTINUE
 210     TADJT = 0.0
         TYJK = 0.0
         TPYJK = 0.0
         K1 = 0

         DO 215 I2=1,3
         DO 215 I=1,NCAUSE
            CUMSF(I2,I) = 0
```

```
 215       CONTINUE

C  COMPUTES THE ADJUSTED # OF TRIALS FROM THE ADJUSTED # OF FAILURES
C  AND COMPUTES THE SUM OF THE ADJUSTED # OF TRIALS FOR ESTIMATE COMP.

        PREL = 0.0
        LTRIAL = 0

C  IF ADJUSTED FAILURES ARE APPROACHING 0 THEN ADJUSTED TRIALS MUST
C  BE PRE-SET.

        DO 240 I=1,J

          IF(A(IADJF,I) .LE. .0000001) THEN
            A(IADJF,I) = .0000001
           ENDIF

          A(IADJT,I) = A(INTR,I)/A(IADJF,I)
          TADJT = TADJT + A(IADJT,I)

C  COMPUTE YJK FROM THE ADJUSTED # OF TRIALS AND STORE THE SUM FOR
C  ESTIMATE COMPUTATION, USE ARRAY FOR # TRIALS < 1000 AND APPROX. FOR
C  VALUES > 1000

          N1 = NINT(A(IADJT,I))
          IF(N1.LE.1000) THEN
              A(IYJK,I) = YJK(N1)
          ELSEIF(N1.GT.1000) THEN
              X=N1
              Q=12*X
              T=X+1
              S=X+2

          A(IYJK,I)=(EUL+(LOG(X))+(1/(2*X))-(1/(Q*T))-(1/(Q*T*S)))

          ELSE
          ENDIF

C  DETERMINE IF A PHASE BOUNDARY HAS BEEN REACHED TO BEGIN ESTIMATE
C  COMPUTATION

      IF(I.EQ.1) GOTO 225
      IF(A(IPHASE,I).NE.A(IPHASE,(I-1))) THEN

C  COMPUTE THE WOODS WEIGHTED AVERAGE ESTIMATE

      MAX = 0
      K1 = K1 + 1

C  DETERMINE THE FAILURE CAUSE WITH THE LARGEST # OF FAILURES

      DO 220 I1=1,NCAUSE
         IF(CUMSF(1,I1).GT.MAX) THEN
         MAX = CUMSF(1,I1)
         ICOL = I1
         ELSE
```

```
      ENDIF
 220  CONTINUE

C COMPUTE YJK VALUE FOR THE CURRENT PHASE ESTIMATE

      IF(CUMSF(1,ICOL).LE.1000) THEN
         AHATL = YJK(CUMSF(1,ICOL))
      ELSEIF(CUMSF(1,ICOL).GT.1000) THEN
         X = CUMSF(1,ICOL)
         Q=12*X
         T=X+1
         S=X+2

         AHATL=(EUL+(LOG(X))+(1/(2*X))-(1/(Q*T))-(1/(Q*T*S)))

      ELSE
      ENDIF
      IX = CUMSF(1,ICOL) + CUMSF(3,ICOL)
      IF(IX.LE.1000) THEN
         AHATU = YJK(IX)
      ELSEIF(IX.GT.1000) THEN
         X = IX
         Q=12*X
         T=X+1
         S=X+2

         AHATU=(EUL+(LOG(X))+(1/(2*X))-(1/(Q*T))-(1/(Q*T*S)))

      ELSE
      ENDIF

C COMPUTE CURRENT PHASE RELIABILITY ESTIMATE

      AHAT = AHATU - AHATL
      CREL = 1.0 - EXP(-AHAT)
      X = CUMSF(1,ICOL) + CUMSF(3,ICOL)

C  COMPUTE AND STORE THE WOODS WEIGHTED AVERAGE ESTIMATE

      PREL = ((LTRIAL*PREL)/X) + (((X-LTRIAL)*CREL)/X)
      LTRIAL = CUMSF(1,ICOL) + CUMSF(3,ICOL)

C  COMPUTE THE PHASE AND GLOBAL AVERAGE FOR YJK USED IN THE EXPONENTIAL
C  REGRESSION ESTIMATES ARE

      REG(2,K1) = TYJK/(I-1)
      REG(3,K1) = TPYJK/NFAPH(K1)
      TPYJK = 0.0

      ENDIF

C  COMPUTE THE NUMBER OF FAILURES AND SUCCESSES FOR EACH FAILURE CAUSE
C  USED IN THE WOODS WEIGHTED AVERAGE ESTIMATE

 225  ICAUSE = INT(A(IFAILC,I)+.5)
      DO 230 I1=1,NCAUSE
```

```
      CUMSF(2,I1) = CUMSF(2,I1) + INT(A(INTR,I) + .5)
      CUMSF(3,I1) = CUMSF(3,I1) + N1
230   CONTINUE
      CUMSF(1,ICAUSE) = CUMSF(1,ICAUSE) + 1
      CUMSF(2,ICAUSE) = CUMSF(2,ICAUSE) - 1
      CUMSF(3,ICAUSE) = CUMSF(3,ICAUSE) - 1
        TPYJK = TPYJK + A(IYJK,I)
        TYJK = TYJK + A(IYJK,I)
240     CONTINUE

C  REPEAT COMPUTATIONS FOR THE WOODS WEIGHTED AVERAGE ESTIMATE FOR THE
C  FINAL PHASE

      MAX = 0
      K1 = K1 + 1
      DO 245 I1=1,NCAUSE
         IF(CUMSF(1,I1).GT.MAX) THEN
         MAX = CUMSF(1,I1)
         ICOL = I1
         ELSE
         ENDIF
245   CONTINUE

      IF(CUMSF(1,ICOL).LE.1000) THEN
         AHATL = YJK(CUMSF(1,ICOL))
      ELSEIF(CUMSF(1,ICOL).GT.1000) THEN
         X = CUMSF(1,ICOL)
         Q=12*X
         T=X+1
         S=X+2

         AHATL=(EUL+(LOG(X))+(1/(2*X))-(1/(Q*T))-(1/(Q*T*S)))

      ELSE
      ENDIF
      IX = CUMSF(1,ICOL) + CUMSF(3,ICOL)
      IF(IX.LE.1000) THEN
         AHATU = YJK(IX)
      ELSEIF(IX.GT.1000) THEN
         X = IX
         Q=12*X
         T=X+1
         S=X+2

         AHATU=(EUL+(LOG(X))+(1/(2*X))-(1/(Q*T))-(1/(Q*T*S)))

      ELSE
      ENDIF

      AHAT = AHATU - AHATL
      CREL = 1.0 - EXP(-AHAT)
      X = CUMSF(1,ICOL) + CUMSF(3,ICOL)


      PREL = ((LTRIAL*PREL)/X) + (((X-LTRIAL)*CREL)/X)
      LTRIAL = CUMSF(1,ICOL) + CUMSF(3,ICOL)
```

```
      REG(2,K1) = TYJK/(J)
      REG(3,K1) = TPYJK/NFAPH(K1)

        PHREST(1,K) = PREL

C  COMPUTE THE MLE ESTIMATE OF PHASE RELIABILITY USING DISCOUNTING

        PHREST(2,K) = (TADJT - J)/TADJT

C  COMPUTE THE EXPONENTIAL REGRESSION ESTIMATE BEGINNING WITH B HAT

         SUM = 0.0
         SUMS = 0.0
         IF (K.EQ.1) GOTO 252
         DO 250 I = 1,K
              SUM = SUM + ((I-REG(1,K))*REG(3,I))
              SUMS = SUMS + ((I-REG(1,K))**2)
 250     CONTINUE

         REG(4,K) = SUM/SUMS

C  COMPUTE A HAT

         REG(5,K) = REG(2,K) - (REG(4,K)*REG(1,K))

C  COMPUTE AND STORE THE EXPONENTIAL REGRESSION ESTIMATE

         PHREST(4,K) = 1.0 - EXP(-(REG(5,K) + (REG(4,K)*K)))
         IF(PHREST(4,K).LT.0.0) PHREST(4,K)=0.0
         GOTO 255
 252     PHREST(4,K) = 1.0 - EXP(-REG(3,1))
         IF(PHREST(4,K).LT.0.0) PHREST(4,K)=0.0


C  STORE THE RUNNING SUM OF THE ESTIMATES FOR THE CURRENT PHASE AND THE
C  RUNNING SUM OF THE ESTIMATES SQUARED FOR COMPUTATION OF THE MEAN AND
C  STANDARD DEVIATION OF EACH ESTIMATE FOR EACH RELIABILITY GROWTH
C  MODEL

 255    EST(1,K) = EST(1,K) + PHREST(1,K)
        EST(2,K) = EST(2,K) + (PHREST(1,K)**2)
        MLEWD(1,K) = MLEWD(1,K) + PHREST(2,K)
        MLEWD(2,K) = MLEWD(2,K) + (PHREST(2,K)**2)
        REGEST(1,K) = REGEST(1,K) + PHREST(4,K)
        REGEST(2,K) = REGEST(2,K) + (PHREST(4,K)**2)

C  COMPUTE THE VARIANCES OF THE UNWEIGHTED EXPONENTIAL REGRESSION
C  ESTIMATES AND STORE THE RUNNING SUM OF THE VARIANCES FOR USE IN THE
C  WEIGHTED REGRESSION MODEL.

      VAR(K)  = (NFAPH(K)*PHREST(1,K))/((1.-PHREST(1,K))**2)
      IF ( VAR(K) .LT. .0000001)THEN
      VAR(K) = .0000001
      END IF
      IF (K .EQ. 1) GO TO 258
      SVAR1(K) = SVAR1(K-1) + (1./VAR(K))
```

```
      SVAR2(K) = SVAR2(K-1) + VAR(K)
      SUMW(K) = SUMW(K-1) + W(3,K)
      GO TO 259
 258  SVAR1(K) = (1./VAR(1))
      SVAR2(K) = VAR(1)
      SUMW(K)  = W(3,1)

C  COMPUTE THE WEIGHTS FOR EACH PHASE
 259  W(1,K) = (1./VAR(K))/SVAR1(K)
      W(2,K) = VAR(K)/SVAR2(K)
C  COMPUTE AND STORE X-BAR(W) AND Y-BAR(W)
      SUMX1 = 0
      SUMY1 = 0
      SUMX2 = 0
      SUMY2 = 0
      SUMX3 = 0
      SUMY3 = 0
      DO 261 I = 1,K
         SUMX1 = SUMX1 + (1./VAR(K))*I
         SUMY1 = SUMY1 + (1./VAR(K))*REG(3,I)
         SUMX2 = SUMX2 + VAR(K)*I
         SUMY2 = SUMY2 + VAR(K)*REG(3,I)
         SUMX3 = SUMX3 + W(3,K)*I
         SUMY3 = SUMY3 + W(3,K)*REG(3,I)


 261  CONTINUE
      WREG1(1,K) = SUMX1/SVAR1(K)
      WREG1(4,K) = SUMY1/SVAR1(K)
      WREG2(1,K) = SUMX2/SVAR2(K)
      WREG2(4,K) = SUMY2/SVAR2(K)
      WREG3(1,K) = SUMX3/SUMW(K)
      WREG3(4,K) = SUMY3/SUMW(K)

C  COMPUTE AND STORE B-HAT(W)

      SUM1  = 0.0
      SUMS1 = 0.0
      SUM2  = 0.0
      SUMS2 = 0.0
      SUM3  = 0.0
      SUMS3 = 0.0
      IF (K .EQ. 1) GO TO 272

      DO 271 I = 1,K
         SUM1  = SUM1 + (W(1,K)*(I-WREG1(1,K))*REG(3,I))
         SUMS1 = SUMS1 + ( W(1,K)*((I-WREG1(1,K))**2))
         SUM2  = SUM2 + (W(2,K)*(I-WREG2(1,K))*REG(3,I))
         SUMS2 = SUMS2 + ( W(2,K)*((I-WREG2(1,K))**2))
         SUM3  = SUM3 + (W(3,K)*(I-WREG3(1,K))*REG(3,I))
         SUMS3 = SUMS3 + ( W(3,K)*((I-WREG3(1,K))**2))
 271  CONTINUE


      WREG1(2,K) = SUM1/SUMS1
      WREG2(2,K) = SUM2/SUMS2
```

```
      WREG3(2,K) = SUM3/SUMS3

C COMPUTE AND STORE  A-HAT(W)

      WREG1(3,K) = WREG1(4,K) - (WREG1(2,K)*WREG1(1,K))
      WREG2(3,K) = WREG2(4,K) - (WREG2(2,K)*WREG2(1,K))
      WREG3(3,K) = WREG3(4,K) - (WREG3(2,K)*WREG3(1,K))


C  COMPUTE AND STORE THE WEIGHTED EXPONENTIAL REGRESSION ESTIMATE

      PHREST(5,K) = 1.0 - EXP(-(WREG1(3,K)+(WREG1(2,K)*K)))
      PHREST(6,K) = 1.0 - EXP(-(WREG2(3,K)+(WREG2(2,K)*K)))
      PHREST(7,K) = 1.0 - EXP(-(WREG3(3,K)+(WREG3(2,K)*K)))

      IF (PHREST(5,K) .LT. 0.0) PHREST(5,K) = 0.0
      IF (PHREST(6,K) .LT. 0.0) PHREST(6,K) = 0.0
      IF (PHREST(7,K) .LT. 0.0) PHREST(7,K) = 0.0
      GO TO 275

  272 PHREST(5,K) = 1.0 - EXP(-WREG1(4,1))
      IF (PHREST(5,K) .LT. 0.0) PHREST(5,K) = 0.0

      PHREST(6,K) = 1.0 - EXP(-WREG2(4,1))
      IF (PHREST(6,K) .LT. 0.0) PHREST(6,K) = 0.0

      PHREST(7,K) = 1.0 - EXP(-WREG3(4,1))
      IF (PHREST(7,K) .LT. 0.0) PHREST(7,K) = 0.0

C STORE THE RUNNING SUM OF THE WEIGHTED ESTIMATES FOR THE CURRENT
C PHASE AND THE RUNNING SUM OF THE ESTIMATES SQUARED FOR COMPUTATION OF
C THE MEAN AND STANDARD DEVIATION OF EACH WEIGHTED ESTIMATE FOR THE
C WEIGHTED EXPONENTIAL REGRESSION MODEL.

  275 WREST1(1,K) = WREST1(1,K) + PHREST(5,K)
      WREST1(2,K) = WREST1(2,K) + (PHREST(5,K)**2)

      WREST2(1,K) = WREST2(1,K) + PHREST(6,K)
      WREST2(2,K) = WREST2(2,K) + (PHREST(6,K)**2)

      WREST3(1,K) = WREST3(1,K) + PHREST(7,K)
      WREST3(2,K) = WREST3(2,K) + (PHREST(7,K)**2)


C  STORE THE ACTUAL PHASE RELIABILITY

        AREL(K) = A(ISYSPR,J)

C  PRINT INTERMEDIATE OUTPUT IF REQUESTED AND THE NUMBER OF REPETITIONS
C  IS NOT GREATER THAN 5

        IF(IOPT.NE.1) GOTO 300
        IF(REP.GT.5) GOTO 300

      WRITE(20,1000) REP,K
```

```
1000 FORMAT(T16,'REPETITION NUMBER: ',I4,'   PHASE NUMBER: ',I4)
     WRITE(20,1010) A(ISYSPR,J)
1010 FORMAT(22X,'ACTUAL COMPONENT RELIABILITY: ',F7.5)
     WRITE(20,1020) PHREST(1,K)
1020 FORMAT(20X,'PREDICTED COMPONENT RELIABILITY: ',F7.5)
     WRITE(20,1022) PHREST(2,K)
1022 FORMAT(20X,'MLE ESTIMATE USING DISCOUNTING: ',F7.5)
     WRITE(20,1025) PHREST(3,K)
1025 FORMAT(18X,'MLE ESTIMATE OF PHASE RELIABILITY: ',F7.5)
     WRITE(20,1027) PHREST(4,K)
1027 FORMAT(14X,'REGRESSION ESTIMATE OF PHASE RELIABILITY: ',F7.5)
     WRITE(20,1028) PHREST(4,K)
1028 FORMAT(14X,'WEIGHTED REG. ESTIMATE ( METHOD 1 )   : ',F7.5)
     WRITE(20,1026) PHREST(5,K)
1026 FORMAT(14X,'WEIGHTED REG. ESTIMATE ( METHOD 2 )   : ',F7.5)
     WRITE(20,1029) PHREST(6,K)
1029 FORMAT(14X,'WEIGHTED REG. ESTIMATE ( METHOD 3 )   : ',F7.5)
     WRITE(20,1030)
1030 FORMAT(' ','     ')
     DO 260 I=1,NCAUSE
       WRITE(20,1035)I,A(I,J),A((I+NCAUSE),J)
1035   FORMAT(12X,'CAUSE: ',I3,'   PR(SUCCESS): ',F7.6,'   # TRIALS: ',
    CF10.0)
260  CONTINUE
     WRITE(20,1036)
1036 FORMAT(' ','     ')
     WRITE(20,1040)
1040 FORMAT(4X,'FAIL #',3X,'FAIL CAUSE',3X,'# TRIALS',3X,'ADJ # FAIL',3
    CX,'ADJ # TRIALS',7X,'YJK')
    DO 270 I=1,J
     WRITE(20,1050)I,A(IFAILC,I),A(INTR,I),A(IADJF,I),A(IADJT,I),A(IYJK
    C,I)
1050 FORMAT(4X,I3,8X,F3.0,7X,F8.0,4X,F8.6,4X,F12.0,3X,F11.4)
270  CONTINUE
     WRITE(20,1060)
1060 FORMAT(' ',///)

300  CONTINUE
C  PRINT EACH OF THE 3 ESTIMATES TO THEIR APPROPRIATE OUTPUT FILE
C  IF REQUESTED

     IF(IOPT1.NE.1) GOTO 401
400  WRITE(40,2000) (PHREST(1,I), I=1,NPHASE)
401  IF(IOPT2.NE.1) GOTO 402
     WRITE(50,2000) (PHREST(2,I), I=1,NPHASE)
402  IF(IOPT3.NE.1) GOTO 403
     WRITE(60,2000) (PHREST(3,I), I=1,NPHASE)
403  IF(IOPT4.NE.1) GOTO 404
     WRITE(70,2000) (PHREST(4,I), I=1,NPHASE)
404  IF(IOPT5.NE.1) GOTO 405
     WRITE(16,2000) (PHREST(5,I), I=1,NPHASE)
405  IF(IOPT5.NE.1) GOTO 406
     WRITE(39,2000) (PHREST(6,I), I=1,NPHASE)
406  IF(IOPT5.NE.1) GOTO 500
     WRITE(49,2000) (PHREST(7,I), I=1,NPHASE)
2000 FORMAT(' ',30(F7.6:1X))
```

```
 500  CONTINUE

C WORKING A MATRIX
      DO 4050 J = 1,(2*NCAUSE)+7
         WRITE(83,*) (A(J,I), I = 1,NFAIL)
 4050  CONTINUE


      DO 4052 J = 1,NCAUSE
         WRITE(88,*) (REG(J,I), I = 1,NPHASE)
 4052  CONTINUE

C  UPON COMPLETION OF ALL REPETITIONS, COMPUTE THE MEAN AND STANDARD
C  DEVIATION OF EACH ESTIMATE FOR EACH PHASE SKIPPING COMPUTATIONS IF
C  ONLY ONE REPETITION IS REQUIRED

      IF (NREP.LE.1) GOTO 601

      DO 600 I=1,NPHASE
      EST(3,I) = EST(1,I)/XNREP
      MLEWD(3,I) = MLEWD(1,I)/XNREP
      MLESP(3,I) = MLESP(1,I)/XNREP
      REGEST(3,I) = REGEST(1,I)/XNREP
      WREST1(3,I) = WREST1(1,I)/XNREP
      WREST2(3,I) = WREST2(1,I)/XNREP
      WREST3(3,I) = WREST3(1,I)/XNREP
      EST(4,I) = SQRT((EST(2,I)-(XNREP*(EST(3,I)**2)))/(XNREP-1))
      MLEWD(4,I) = SQRT((MLEWD(2,I)-(XNREP*(MLEWD(3,I)**2)))/(XNREP-1))
      MLESP(4,I) = SQRT((MLESP(2,I)-(XNREP*(MLESP(3,I)**2)))/(XNREP-1))
      REGEST(4,I)=SQRT((REGEST(2,I)-(XNREP*(REGEST(3,I)**2)))/(XNREP-1))
      WREST1(4,I)=SQRT((WREST1(2,I)-(XNREP*(WREST1(3,I)**2)))/(XNREP-1))
      WREST2(4,I)=SQRT((WREST2(2,I)-(XNREP*(WREST2(3,I)**2)))/(XNREP-1))
      WREST3(4,I)=SQRT((WREST3(2,I)-(XNREP*(WREST3(3,I)**2)))/(XNREP-1))
 600  CONTINUE

C  PRINT THE FINAL OUTPUT TABLE TO A FILE

 601  WRITE(30,3000)
 3000 FORMAT('0',T47,'DISCRETE RELIABILITY GROWTH SIMULATION')
      WRITE(30,3010)
 3010 FORMAT('-',T54,'MODEL PARAMETER SUMMARY')
      WRITE(30,3020) NCAUSE
 3020 FORMAT('0',T47,'NUMBER OF POSSIBLE FAILURE CAUSES ',I4)
      IF (FRELOP .EQ. 1) GOTO 4000
      WRITE(30,3030)
 3030 FORMAT('0',T38,'CAUSE NUMBER',T64,'SINGLE TRIAL PR( SUCCESS ) FOR
     CPHASE 1')
      DO 3050 M=1,NCAUSE
      WRITE(30,3040) M,A(M,1)
 3040 FORMAT(' ',T43,I2,T79,F8.6)
 3050 CONTINUE
      WRITE(30,3060) FRIMP
 3060 FORMAT('0',T37,'FRACTION CAUSE RELIABILITY IMPROVES AFTER FAILURE
     C',F8.6)
 5000 WRITE(30,3080) NPHASE
```

```
3080 FORMAT('-',T48,'NUMBER OF PHASES IN THE SIMULATION ',I2)
     WRITE(30,3090)
3090 FORMAT('0',T42,'PHASE NUMBER',T59,'NUMBER OF FAILURES IN THE FIRST
    C PHASE')
     DO 3110 M=1,NPHASE
     WRITE(30,3100) M,NFAPH(M)
3100 FORMAT(' ',T43,I2,T73,I2)
3110 CONTINUE
     WRITE(30,3120) NFAIL
3120 FORMAT('0',T51,'TOTAL NUMBER OF FAILURES ',I4)
     IF(DISOPT.EQ.2) GO TO 3160
     WRITE(30,3130)
3130 FORMAT('-',T38,'DISCOUNTING PERFORMED USING THE CONSTANT FRACTION
    CMETHOD')
     WRITE(30,3140) R
3140 FORMAT('0',T44,'FRACTION EACH FAILURE IS DISCOUNTED ',F8.6)
     WRITE(30,3150) N
3150 FORMAT(' ',T33,'NUMBER OF TRIALS AFTER A FAILURE BEFORE A DISCOUNT
    C IS APPLIED ',I4)
     GO TO 3190
3160 WRITE(30,3170)
3170 FORMAT('-',T44,'DISCOUNTING PERFORMED USING THE LLOYD METHOD')
     WRITE(30,3180) GAMA
3180 FORMAT('0',T39,'PERCENT C.I. ( USED AS DISCOUNT FRACTION ) ',F8.6
    C)
     WRITE(30,3185) LDI
3185 FORMAT('0',T50,'LLOYD DISCOUNT INTERVAL: ',I3)
3190 WRITE(30,3200) DSEED1
3200 FORMAT('-',T46,'RANDOM NUMBER SEED USED ',F15.2)
     WRITE(30,3210) NREP
3210 FORMAT('0',T37,'NUMBER OF REPETITIONS OF THE SIMULATION PERFORMED
    C',I7)
     WRITE(30,3220)
3220 FORMAT('1',T61,'ESTIMATOR:')
     WRITE(30,3230)
3230 FORMAT('0',T48,'SINGLE PHASE MLE WITHOUT DISCOUNTING')
     WRITE(30,3240)
3240 FORMAT('-',T60,'MEAN',T83,'ESTIMATE',T109,'95 %')
     WRITE(30,3250)
3250 FORMAT(' ',T12,'PHASE NUMBER',T29,'ACTUAL RELIABILITY',T52,'PREDIC
    CTED RELIABILITY',T78,'STANDARD DEVIATION',T101,'CONFIDENCE INTERVA
    CL')

C  COMPUTE C.I. FOR SINGLE PHASE MLE

     DO 3270 M=1,NPHASE
     CI = (1.96*MLESP(4,M))/SQRT(XNREP)
     CIU = MLESP(3,M) + CI
     CIL = MLESP(3,M) - CI
     WRITE(30,3260) M,AREL(M),MLESP(3,M),MLESP(4,M),CIL,CIU
3260 FORMAT('0',T17,I2,T34,F8.6,T58,F8.6,T82,F9.6,T99,'( ',F8.6,' , ',F
    C8.6,' )')
3270 CONTINUE
     WRITE(30,3220)
     WRITE(30,3280)
3280 FORMAT('0',T42,'MAX LIKELIHOOD ESTIMATE USING DISCOUNTED FAILURES'
```

```
     C)
      WRITE(30,3240)
      WRITE(30,3250)

C  COMPUTE C.I. FOR MLE WITH DISCOUNTING

      DO 3290 M=1,NPHASE
      CI = (1.96*MLEWD(4,M))/SQRT(XNREP)
      CIU = MLEWD(3,M) + CI
      CIL = MLEWD(3,M) - CI
      WRITE(30,3260) M,AREL(M),MLEWD(3,M),MLEWD(4,M),CIL,CIU
 3290 CONTINUE
      WRITE(30,3220)
      WRITE(30,3300)
 3300 FORMAT('0',T38,'WEIGHTED AVERAGE ESTIMATE USING FAILURE DISCOUNTIN
     CG')
      WRITE(30,3240)
      WRITE(30,3250)

C  COMPUTE C.I. FOR WOODS WEIGHTED AVERAGE ESTIMATES

      DO 3310 M=1,NPHASE
      CI = (1.96*EST(4,M))/SQRT(XNREP)
      CIU = EST(3,M) + CI
      CIL = EST(3,M) - CI
      WRITE(30,3260) M,AREL(M),EST(3,M),EST(4,M),CIL,CIU
 3310 CONTINUE

      WRITE(30,3220)
      WRITE(30,3320)
 3320 FORMAT('0',T43,'REGRESSION ESTIMATE USING DISCOUNTED FAILURES')
      WRITE(30,3240)
      WRITE(30,3250)

C  COMPUTE C.I. FOR EXPONENTIAL REGRESSION ESTIMATES

      DO 3330 M=1,NPHASE
      CI = (1.96*REGEST(4,M))/SQRT(XNREP)
      CIU = REGEST(3,M) + CI
      CIL = REGEST(3,M) - CI
      WRITE(30,3260) M,AREL(M),REGEST(3,M),REGEST(4,M),CIL,CIU
 3330 CONTINUE


C-----WEIGHTED REGRESSION   (METHOD 1)
      WRITE(30,3220)
      WRITE(30,3321)
 3321 FORMAT('0',T43,'WEIGHTED REGRESSSION ESTIMATE (METHOD 1 )')

      WRITE(30,3240)
      WRITE(30,3250)

C  COMPUTE C.I. FOR WEIGHTED EXPONENTIAL REGRESSION ESTIMATES

      DO 3331 M=1,NPHASE
      CI = (1.96*WREST1(4,M))/SQRT(XNREP)
```

```
      CIU = WREST1(3,M) + CI
      CIL = WREST1(3,M) - CI
      WRITE(30,3260) M,AREL(M),WREST1(3,M),WREST1(4,M),CIL,CIU
 3331 CONTINUE

C-----WEIGHTED REGRESSION  (METHOD 2)
      WRITE(30,3220)
      WRITE(30,3322)
 3322 FORMAT('0',T43,'WEIGHTED REGRESSION ESTIMATE (METHOD 2) ')

      WRITE(30,3240)
      WRITE(30,3250)

C  COMPUTE C.I. FOR WEIGHTED EXPONENTIAL REGRESSION ESTIMATES

      DO 3332 M=1,NPHASE
      CI = (1.96*WREST2(4,M))/SQRT(XNREP)
      CIU = WREST2(3,M) + CI
      CIL = WREST2(3,M) - CI
      WRITE(30,3260) M,AREL(M),WREST2(3,M),WREST2(4,M),CIL,CIU
 3332 CONTINUE

C-----WEIGHTED REGRESSION  (METHOD 3)
      WRITE(30,3220)
      WRITE(30,3323)
 3323 FORMAT('0',T43,'WEIGHTED REGRESSION ESTIMATE (METHOD 3) ')

      WRITE(30,3240)
      WRITE(30,3250)

C  COMPUTE C.I. FOR WEIGHTED EXPONENTIAL REGRESSION ESTIMATES

      DO 3333 M=1,NPHASE
      CI = (1.96*WREST3(4,M))/SQRT(XNREP)
      CIU = WREST3(3,M) + CI
      CIL = WREST3(3,M) - CI
      WRITE(30,3260) M,AREL(M),WREST3(3,M),WREST3(4,M),CIL,CIU
 3333 CONTINUE

      WRITE(30,3340)
 3340 FORMAT('1',T59,'RECAPITULATION'//)
      WRITE(30,3350)
 3350 FORMAT('-',T3,'PHASE',T11,'ACTUAL',T28,'MEAN',T38,'EST',T50,'MEAN'
     C,T62,'EST',T72,'MEAN',T82,'EST',T92,'MEAN',T102,'EST',T112
     C,'MEAN',T122,'EST')
      WRITE(30,3360)
 3360 FORMAT(' ',T11,'RELIAB',T28,'WGT',T38,'STD',T50,'MLE',T62,'STD',T7
     C2,'PHASE',T82,'STD',T92,'REG',T102,'STD',T112,'WT',T122,'STD')
      WRITE(30,3370)
 3370 FORMAT(' ',T28,'AVG',T38,'DEV',T50,'W/D',T62,'DEV',T72
     C,'MLE',T82,'DEV',T92,'EST',T102,'DEV',T112,'REG',T122,'DEV')
      WRITE(30,3375)
 3375 FORMAT(' ',T28,'EST',T112,'(1)'/)
      DO 650 I=1,NPHASE
        WRITE(30,3380)I,AREL(I),EST(3,I),EST(4,I),MLEWD(3,I),MLEWD(4,I),
     CMLESP(3,I),MLESP(4,I),REGEST(3,I),REGEST(4,I),WREST1(3,I),
```

```
     CWREST1(4,I)
 3380 FORMAT('0',T4,I3,T11,F7.6,T26,F7.6,T36,F7.6,T50,F7.6,T62,F7.6,T72,
     CF7.6,T82,F7.6,T92,F7.6,T102,F7.6,T112,F7.6,T122,F7.6)

 650  CONTINUE

C-----PAGE 2 OF RECAPITULATION:

      WRITE(30,3381)
 3381 FORMAT('1',T59,'RECAPITULATION CONT.'//)

      WRITE(30,3382)
 3382 FORMAT('-',T3,'PHASE',T11,'ACTUAL',T28,'MEAN',T38,'EST',T53,
     C'MEAN',T63,'EST',T78,'MEAN',T88,'EST',T103,'MEAN',T113,'EST')
      WRITE(30,3383)
 3383 FORMAT(' ',T11,'RELIAB',T28,'REG',T38,'STD',T53,'METHOD',T63,
     C'STD',T77,'METHOD',T88,'STD',T103,'METHOD',T113,'STD')
      WRITE(30,3384)
 3384 FORMAT(' ',T28,'EST',T35,'DEVIATION',T53,'ONE',T60,'DEVIATION'
     C,T78,'TWO',T85,'DEVIATION',T103,'THREE',T110,'DEVIATION')
      DO 651 I=1,NPHASE
      WRITE(30,3385) I,AREL(I),REGEST(3,I),REGEST(4,I),WREST1(3,I)
     C,WREST1(4,I),WREST2(3,I),WREST2(4,I),WREST3(3,I),WREST3(4,I)
 3385 FORMAT('0',T4,I3,T11,F7.6,T26,F7.6,T36,F7.6,T51,F7.6,T61,F7.6
     C,T76,F7.6,T86,F7.6,T101,F7.6,T111,F7.6)

      WRITE (53,3400) MLEWD(4,I)
      WRITE (54,3400) MLEWD(3,I)

      WRITE (63,3400) MLESP(4,I)
      WRITE (64,3400) MLESP(3,I)

      WRITE (73,3400) REGEST(4,I)
      WRITE (74,3400) REGEST(3,I)

      WRITE(17,3400) WREST1(4,I)
      WRITE(18,3400) WREST1(3,I)
      WRITE(93,3400) WREST2(4,I)
      WRITE(94,3400) WREST2(3,I)
      WRITE(95,3400) WREST3(4,I)
      WRITE(96,3400) WREST3(3,I)

      WRITE (84,3400) AREL(I)

 3400 FORMAT(' ',F7.6)

 651  CONTINUE


      GO TO 6000

 4000 WRITE(30,4010)
 4010 FORMAT(1X,//,T50,'FIXED PHASE RELIABILITY OPTION')
      WRITE(30,4020)
 4020 FORMAT('-',T38,'PHASE NUMBER',T78,'ACTUAL RELIABILITY')
      DO 4030 M=1,NPHASE
```

```
      WRITE(30,4040) M,AREL(M)
4040 FORMAT('0',T41,I2,T83,F8.6)
4030 CONTINUE
     GO TO 5000
6000 CONTINUE

     STOP
     END
```

5. SAMPLE OUTPUT FROM DRG FORTRAN A1

DISCRETE RELIABILITY GROWTH SIMULATION

MODEL PARAMETER SUMMARY

NUMBER OF POSSIBLE FAILURE CAUSES 5

FIXED PHASE RELIABILITY OPTION

PHASE NUMBER	ACTUAL RELIABILITY
1	0.398418
2	0.428109
3	0.480793
4	0.539243
5	0.609949
6	0.702683
7	0.798124
8	0.899963
9	0.950990
10	0.990040

NUMBER OF PHASES IN THE SIMULATION 10

PHASE NUMBER	NUMBER OF FAILURES IN THE FIRST PHASE
1	1
2	1
3	1
4	1
5	1
6	1
7	1
8	1
9	1
10	1

TOTAL NUMBER OF FAILURES 10

DISCOUNTING PERFORMED USING THE CONSTANT FRACTION METHOD

FRACTION EACH FAILURE IS DISCOUNTED 0.000000
NUMBER OF TRIALS AFTER A FAILURE BEFORE A DISCOUNT IS APPLIED 1

RANDOM NUMBER SEED USED 624712.00

NUMBER OF REPETITIONS OF THE SIMULATION PERFORMED 500

ESTIMATOR:

SINGLE PHASE MLE WITHOUT DISCOUNTING

PHASE NUMBER	ACTUAL RELIABILITY	MEAN PREDICTED RELIABILITY	ESTIMATE STANDARD DEVIATION	95 % CONFIDENCE INTERVAL
1	0.398418	0.218340	0.295824	(0.192410 , 0.244270)
2	0.428109	0.273148	0.314961	(0.245540 , 0.300755)
3	0.480793	0.274906	0.307863	(0.247921 , 0.301892)
4	0.539243	0.335171	0.334579	(0.305844 , 0.364498)
5	0.609949	0.377466	0.338815	(0.347767 , 0.407164)
6	0.702683	0.502564	0.325138	(0.474065 , 0.531064)
7	0.798124	0.600890	0.323988	(0.572491 , 0.629289)
8	0.899963	0.746857	0.269689	(0.723217 , 0.770496)
9	0.950990	0.843546	0.232200	(0.823193 , 0.863899)
10	0.990040	0.952865	0.127951	(0.941650 , 0.964081)

ESTIMATOR:

MAX LIKELIHOOD ESTIMATE USING DISCOUNTED FAILURES

PHASE NUMBER	ACTUAL RELIABILITY	MEAN PREDICTED RELIABILITY	ESTIMATE STANDARD DEVIATION	95 % CONFIDENCE INTERVAL
1	0.398418	0.218340	0.295824	(0.192410 , 0.244270)
2	0.428109	0.273148	0.314961	(0.245540 , 0.300755)
3	0.480793	0.274906	0.307863	(0.247921 , 0.301892)
4	0.539243	0.335171	0.334579	(0.305844 , 0.364498)
5	0.609949	0.377466	0.338815	(0.347767 , 0.407164)
6	0.702683	0.502564	0.325138	(0.474065 , 0.531064)
7	0.798124	0.600890	0.323988	(0.572491 , 0.629289)
8	0.899963	0.746857	0.269689	(0.723217 , 0.770496)
9	0.950990	0.843546	0.232200	(0.823193 , 0.863899)
10	0.990040	0.952865	0.127951	(0.941650 , 0.964081)

ESTIMATOR:

REGRESSION ESTIMATE USING DISCOUNTED FAILURES

PHASE NUMBER	ACTUAL RELIABILITY	MEAN PREDICTED RELIABILITY	ESTIMATE STANDARD DEVIATION	95 % CONFIDENCE INTERVAL
1	0.398418	0.261067	0.348656	(0.230506 , 0.291628)
2	0.428109	0.323922	0.367297	(0.291727 , 0.356117)
3	0.480793	0.387379	0.306992	(0.360470 , 0.414288)
4	0.539243	0.449910	0.295458	(0.424012 , 0.475808)
5	0.609949	0.504971	0.284013	(0.480076 , 0.529866)
6	0.702683	0.600917	0.250502	(0.578960 , 0.622874)
7	0.798124	0.702346	0.198444	(0.684952 , 0.719741)
8	0.899963	0.813700	0.129989	(0.802306 , 0.825094)
9	0.950990	0.891043	0.091377	(0.883033 , 0.899052)
10	0.990040	0.957506	0.038794	(0.954106 , 0.960907)

ESTIMATOR:

WEIGHTED REGRESSSION ESTIMATE (METHOD 1)

PHASE NUMBER	ACTUAL RELIABILITY	MEAN PREDICTED RELIABILITY	ESTIMATE STANDARD DEVIATION	95 % CONFIDENCE INTERVAL
1	0.398418	0.261067	0.348656	(0.230506 , 0.291628)
2	0.428109	0.435318	0.354942	(0.404206 , 0.466430)
3	0.480793	0.491709	0.281109	(0.467069 , 0.516349)
4	0.539243	0.546405	0.253105	(0.524219 , 0.568590)
5	0.609949	0.590791	0.230129	(0.570619 , 0.610962)
6	0.702683	0.658504	0.207403	(0.640324 , 0.676684)
7	0.798124	0.738407	0.167540	(0.723721 , 0.753092)
8	0.899963	0.833221	0.114830	(0.823155 , 0.843286)
9	0.950990	0.897713	0.079087	(0.890781 , 0.904646)
10	0.990040	0.951244	0.036190	(0.948072 , 0.9544;6)

ESTIMATOR:

WEIGHTED REGRESSION ESTIMATE (METHOD 2)

PHASE NUMBER	ACTUAL RELIABILITY	MEAN PREDICTED RELIABILITY	ESTIMATE STANDARD DEVIATION	95 % CONFIDENCE INTERVAL
1	0.398418	0.261067	0.348656	(0.230506 , 0.291628)
2	0.428109	0.427212	0.367692	(0.394983 , 0.459442)
3	0.480793	0.482696	0.310341	(0.455493 , 0.509898)
4	0.539243	0.547323	0.283738	(0.522453 , 0.572194)
5	0.609949	0.596459	0.265281	(0.573206 , 0.619712)
6	0.702683	0.680009	0.236573	(0.659273 , 0.700746)
7	0.798124	0.779319	0.196985	(0.762052 , 0.796585)
8	0.899963	0.889988	0.143688	(0.877393 , 0.902583)
9	0.950990	0.957167	0.095822	(0.948768 , 0.965566)
10	0.990040	0.997026	0.024431	(0.994885 , 0.999168)

ESTIMATOR:

WEIGHTED REGRESSION ESTIMATE (METHOD 3)

PHASE NUMBER	ACTUAL RELIABILITY	MEAN PREDICTED RELIABILITY	ESTIMATE STANDARD DEVIATION	95 % CONFIDENCE INTERVAL
1	0.398418	0.261067	0.348656	(0.230506 , 0.291628)
2	0.428109	0.323922	0.367297	(0.291727 , 0.356117)
3	0.480793	0.387379	0.306992	(0.360470 , 0.414288)
4	0.539243	0.449910	0.295458	(0.424012 , 0.475808)
5	0.609949	0.504971	0.284013	(0.480076 , 0.529865)
6	0.702683	0.872946	0.170618	(0.857990 , 0.887901)
7	0.798124	0.866622	0.118914	(0.856198 , 0.877045)
8	0.899963	0.872074	0.088072	(0.864354 , 0.879794)
9	0.950990	0.943671	0.052325	(0.939085 , 0.948258)
10	0.990040	0.957422	0.034210	(0.954423 , 0.960420)

il

RECAPITULATION

PHASE	ACTUAL RELIAB	MEAN NI REG EST	EST STD DEVIATION	MEAN MLE N/D	EST STD DEVIATION	MEAN PHASE MLE	EST STD DEVIATION	MEAN REG EST	EST STD DEVIATION
1	.398418	.261067	.348656	.218340	.295824	.218340	.295824	.261067	.348656
2	.428109	.435318	.354942	.273148	.314961	.273148	.314961	.323922	.367297
3	.480793	.491709	.281109	.274906	.307863	.274906	.307863	.387379	.306992
4	.539243	.546405	.253105	.335171	.334579	.335171	.334579	.449910	.295458
5	.609949	.590791	.230129	.377466	.338815	.377466	.338815	.504971	.284013
6	.702683	.658504	.207403	.502564	.325138	.502564	.325138	.600917	.250502
7	.798124	.738407	.167540	.600890	.323988	.600890	.323988	.702346	.198444
8	.899963	.833221	.114830	.746857	.269689	.746857	.269689	.813700	.129989
9	.950990	.897713	.079087	.843546	.232200	.843546	.232200	.891043	.091377
10	.990040	.951244	.036190	.952865	.127951	.952865	.127951	.957506	.038794

RECAPITULATION CONT.

PHASE	ACTUAL RELIAB	MEAN REG EST	EST STD DEVIATION	MEAN METHOD ONE	EST STD DEVIATION	MEAN METHOD TWO	EST STD DEVIATION	MEAN METHOD THREE	EST STD DEVIATION
1	.398418	.261067	.348656	.261067	.348656	.261067	.348656	.261067	.348656
2	.428109	.323922	.367297	.435318	.354942	.427212	.367692	.323922	.367297
3	.480793	.387379	.306992	.491709	.281109	.482696	.310341	.387379	.306992
4	.539243	.449910	.295458	.546405	.253105	.547323	.283738	.449910	.295458
5	.609949	.504971	.284013	.590791	.230129	.596459	.265281	.504971	.284013
6	.702683	.600917	.250502	.658504	.207403	.680009	.236573	.872946	.170618
7	.798124	.702346	.198444	.738407	.167540	.779319	.196985	.866622	.118914
8	.899963	.813700	.129989	.833221	.114830	.889988	.143688	.872074	.088072
9	.950990	.891043	.091377	.897713	.079087	.957167	.095822	.943671	.052325
10	.990040	.957506	.038794	.951244	.036190	.997026	.024431	.957422	.034210

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