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FOREWORD

The fluid amplifier reliability procedure work described in this report was carried out as Phase IV and as Task 3, Phase V, of a National Aeronautics and Space Administration fluid amplifier program, "Research and Development - Fluid Amplifiers and Logic". (Contract NAS 8-5408). The work was sponsored by the Astrionics Laboratory at the George C. Marshall Space Flight Center, Huntsville, Alabama. This project originated under the technical direction of Mr. R. E. Currie and subsequently was under the technical direction of Mr. J. A. Peoples.

The work was conducted at the Mechanical Technology Laboratory, General Electric Research and Development Center, in Schenectady, New York. Mr. R. C. Bowlin was the project engineer and Dr. J. N. Shinn provided technical direction. In addition to the authors, other major contributors to the program were Messrs. A. R. Adler, R. K. Rose, and H. W. Avery.

ABSTRACT

This report summarizes the work performed to develop initial procedures by which data may be gathered and on which an assessment of fluid amplifier reliability may be made. A specific test directed toward evaluating the reliability of fluid amplifiers and a generalized failure report form have been developed. Recommendations have been submitted for procedural improvements and expanded scope, to better understand the physics of fluid amplifier failures.

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Section 1

INTRODUCTION

Apparent advantages with respect to the failure mechanisms inherent in competing devices are by themselves insufficient proof of fluid amplifier reliability. A procedure must be developed by which data may be gathered in an orderly fashion, and on which an accurate assessment of fluid amplifier reliability may be made independent of competitive devices. The primary emphasis of this program was directed toward establishing such a procedure.

Up to now, a fundamental consideration in the choice of fluid amplifiers for applications (such as logic devices and control systems) has been the intuitive conclusion that fluid amplifiers will offer substantially increased reliability over other devices that might be called upon to perform similar functions. This intuitive judgement is based on an understanding of how conventional hydraulic, pneumatic, or electronic devices fail, and on the easily descernible immunity of fluid logic to those mechanisms of failure.

It was apparent that the absence of moving parts precludes the conventional aspects of friction induced by sliding or rolling parts. It was also evident that the functional integrity of fluid amplifiers is not dependent on the choice of a particular material, but that material selection could be adapted to the needs of environmental constraints. For example, the effect of radiation, which is apparent in silicon semiconductors, could be minimized through material selection processes since the fluid amplifier characteristic is a function of its geometry and since the material need only be inert relative to the transport fluid.

Section 2

SYNOPSIS

2.1 PROGRAM PLAN

To develop procedures for gathering information with which an assessment of fluid amplifier reliability may be made, one must recognize that in general, reliability data can be obtained from two sources:

1. Specific reliability tests to obtain failure data under known and controlled conditions .
2. Failure reports gathered from various programs aimed at research or device development; that is, programs not specifically aimed at reliability work.

2.1.1 RELIABILITY TEST PROCEDURE

This program concentrated on failures in digital devices because: 1) a digital failure could clearly be defined, and 2) definition of failure in analog devices (e.g., degradation of gain or response) becomes difficult unless catastrophic. The test device selected was a series stack of digital elements referred to as a serial shift register with the output connected back to the input so that it stored information on application of clock pulses (for element selection details see Appendix C). The register capacity was five bits; each clock pulse advanced the stored number or digit order by one bit so that after five clock pulses the register again contained the initially set five-bit word. Six such registers were continuously clocked at a 120 cycle per second pulse rate. Thus, the digital fluid amplifier elements switched as the preset number circulated through the shift register at the rate of approximately 2.07×10^6 times per day.

The following plan was followed to study failure rates:

Phase I - Operation at design conditions

Phase II - Operation at "stressed" conditions

Phase III - Retest at design conditions.

In Phase II, the stresses were changes in operating parameters most likely to be encountered with fluid amplifier circuits in a practical application. The parameters, their design values, and the stress values are shown in Table 1.

The procedures were refined as the test work proceeded and the failure data investigated to determine its statistical significance (procedural changes of any significance occurred subsequent to Phase II).

Table 1

CHANGES IN OPERATING PARAMETERS

Operating Parameter	Design Value	Stress Value
Supply gas pressure	Flip-flop - 1.5 psig Gate - 2.0 psig	25 percent decrease
Supply gas temperature	70° F	160° F
Environment contamination	Room air ambient	10 ml Arizona road dust

The Phase III testing was carried out to learn if any permanent damage had occurred because of testing at stressed conditions. Finally, the test devices which produced the greatest failure rates as a result of the "stress" tests were torn down to learn if the physics of the failures could be determined.

2.1.2 FAILURE REPORTS

Failures of fluid amplifier elements in programs at the General Electric Research and Development Center were documented on a standard report form (see Appendix B) developed during this reliability program. The intent of this failure recording was not to establish procedure; but, rather to develop reporting techniques amenable to collecting data from a large variety of sources. In order to encourage reporting, the form is a brief, one page document which could be quickly completed. Although the failure reporting form was developed and modified once during this program in an attempt to cover all reported failures, it is not yet considered all-inclusive. It is expected that additional refinement and updating will be necessary when this reporting procedure is implemented.

2.2 SUMMARY OF RESULTS

A fluid amplifier standard report form has been developed by which information pertinent to fluid amplifier reliability may be collected. Failures reported on fluid amplifier standard report forms, from development programs at the Research and Development Center, appear primarily due to manufacturing techniques which at the present state-of-the-art are not necessarily optimum. At this time there is little or no history with which failure trends may be established. (See Appendix B)

A basic test procedure has been established by which accurate reliability information may be gathered for digital fluid amplifiers. Observations based on preliminary data are as follows:

1. Failures appear to be nonrandom in that certain patterns were more predominant than others while, in general, failure rates varied with time.

2. Data from some (but not all) shift registers suggest a higher failure rate under increased temperature. Further, there is no clear cut evidence that pressure or contamination lead to any changes in mean time to failure or that residual effects from previous stress conditions exist.

3. A substantial variability existed in the number of failures between shift registers. In general, however, a total of 51 failures occurred in 486 shift register test days at standard room temperature conditions while 57 failures occurred in 294 shift register test days at stressed environmental conditions. (As noted before, 2.07×10^6 switch cycles occur in one shift register test day.)

2.3 CONCLUSIONS

It has been concluded that the test procedure developed, when properly monitored, is one successful approach by which accurate reliability information may be gathered. By requiring each shift register to hold the same digit order, the likelihood of failure is the same for each register, and the effect of geometry or stress level may be evaluated independently of a variable probability of failure. A measure of the element memory reliability may be evaluated separately from its ability to switch when it is required that each shift register hold a digit order, which does not require switching between digits. Finally, the significance of switching sequence may be evaluated by changing the digit order on all registers to all possible combinations of digit orders (some digit orders have higher probabilities of failure).

Perhaps the most notable conclusion derived from the preliminary data in this program is that shift register failures (the inability to hold an input number) occur in clearly nonrandom or preferential patterns. Although it is not known specifically which variables (environmental or geometric) affect this phenomenon, several statements may be made. First, failures occurred clustered in time irrespective of prior test duration. This tends to contradict the assumption that infant mortality or burn-in periods will eliminate such clustering. Second, shift registers of the same design reacted differently to changes in environmental conditions.

It may be concluded, therefore, that environmental trends or patterns applicable to all the digital amplifiers were not established. It does indicate, however, that one or both of the following may apply. Either the changes in stress level were insufficient in magnitude and therefore inconclusive, or the likelihood exists that manufacturing processes and tolerances are extremely critical and strongly influence the amplifiers' susceptibility and trend relative to environmental changes. The latter is probably more accurate. The considerable variation in failure rate demonstrated between shift registers at the same level of stress and in the same environment is probably related to the manufacturing process.

Statistically, the data gathered is preliminary, limited in quantity, and therefore doubtful as to its credibility as being truly representative of the fluid amplifier population. It represents the first point on a history curve. What is important, however, is the creation and demonstration of a test procedure or approach which will permit future programs to expand on this beginning.

2.4 RECOMMENDATIONS

In order to achieve a better understanding of the physics of fluid amplifier failure and expand upon the knowledge already obtained, the following recommendations are made.

1. Work should be performed to understand which amplifier characteristics are critical and most significantly affect failure rate. Of interest is the sensitivity of switching level (control pressure) and element gain (discharge pressure) to geometric changes of the interaction region, and flow level.

2. To understand the physical significance of the apparent non-random failure patterns, work should be performed to determine the sequence of events which occur when a failure takes place. First, instrumentation should be increased in scope to ascertain if serial shift register failures occur consistently because of a particular element in that stack. Then, transient instrumentation may be applied to the suspect element and a like element which does not malfunction to compare the sequence of events that occur during the switching process.

3. Test equipment should be modified to include a system of time marking signals, so that the selection of digit orders can be expanded to include all possible combinations and evaluate each probability of failure.

4. A set of "Acceptance Test" limits should be developed to define acceptable operation of an analog element which might be shipped as a production unit. Testing as outlined above should then be performed to determine the analog element "characteristic sensitivities" to geometry changes (possibly due to erosion) or variable source pressures (possibly due to leaks).

Section 3

METHOD OF APPROACH

3.1 PROGRAM PHILOSOPHY

Conventional reliability assessments direct themselves toward the establishment of a "Reliability Figure of Merit", such as failure rate or mean time between failure, based on the statistical evaluation of a meaningful sample. This sample, tested under controlled environments, provides such measurements with some measure of statistical "confidence". Further these test programs generally require a product maturity that allows the treatment of failure events as a random occurrence or, in rare instances, as being associated with some other (but equally well-defined) distributional assumption.

Because of the early development status of fluid amplifiers, this preliminary investigation of fluid amplifier failure rates attempts to do more than establish an initial point on the reliability growth curve and informs on the devices' reliability potential. This program directs itself toward: 1) establishing meaningful reliability testing procedures where the ultimate goal is increased understanding of the physics of failure of fluid amplifiers; 2) providing preliminary information useful in assessing inherent reliability; and 3) providing guidance in determining areas of weakness and therefore areas of emphasis during continuing program development.

3.2 FACTORS AFFECTING RELIABILITY - DEFINITIONS

In order to evaluate the failure mechanisms that might be appropriate for investigation at this time, it was decided to classify all potential failure types into five major categories. Only those appropriate during early development were considered during the program. The five failure mechanisms are identified as:

1. Mean Basic
2. Mean Contaminant
3. Variants
4. Freaks
5. Abnormal Environments

3.2.1 MEAN BASIC

This category is defined as the one where the mean strength or mean life is limited by the properties of the basic constituent materials of the part.

The problems in this category are not related to variability from specimen to specimen nor are they subject to external contaminants. The important feature of this category is that it is dependent on the physical properties of the basic material or the basic design and that it is likely to be a limiting factor in all components and not just in a small percentile of the population. An example of a "Mean Basic" failure in fluid amplifiers might be the fatigue failure of a thin section due to inadequate stress margins. Control of mean basic failure mechanisms therefore must be undertaken during the initial development of the product and cannot be improved by process or quality control.

3.2.2 MEAN CONTAMINANT

The category described as mean contaminant while relating to mean strength or mean life, concerns itself with the influence of a foreign or contaminating material. In the case of fluid amplifiers, contaminants exist to a greater or lesser degree in all fluids; but, unlike the mean basic category, the opportunity exists for varying the amount of contaminant without a change in basic materials. The erosion of sharp edges by contaminants in the transport fluid would be a typical example of this category.

3.2.3 VARIANTS

This category relates to the limitation of strength or life due to the effect of statistical variability within the population. It is often the result of a poorly controlled manufacturing process, and many examples of the life limiting effects of variability can be cited; for example, a fluid amplifier failure of this type might be due to dimensional variability and bond strength. These types of failures should not be considered during an early developmental program.

3.2.4 FREAKS

The category of freaks includes those failures which are not representative of the test lot. Very often these freaks are sorted out during infant mortality checks such as run-in or burn-in. In the case of fluid amplifiers, such freaks would include gross leakage at interconnections or failure to drill a control port.

3.2.5 ABNORMAL ENVIRONMENTS

In this category failure occurs due to abnormal usage conditions. This type of failure mechanism is usually not exposed by in-house testing but by a post mortem analysis. An example of this type of failure could be from operation in a pressure range in excess of those specified for a particular fluid amplifier design.

In the initial analysis appropriate for investigation during this phase of the program, consideration of failures resulting from the so-called freak have been eliminated. Primary emphasis has been placed on the Mean Basic, Mean Contaminant, and Abnormal Environment categories with little consideration being given to those failure mechanisms that are primarily a question of production or process control.

3.3 ESTABLISHING THE TEST PROCEDURE

The establishment of a test procedure required the selection of meaningful failure parameters that could be observed and easily monitored during a detailed test program. This was accomplished by reviewing with selected laboratory personnel, engineers, and technicians the results from prior individual element tests. For example:

1. Previous modes of failures,
2. The mechanism potentially responsible for such failure, and
3. Other failure modes and mechanisms that could be postulated.

This review disclosed a variety of possible failure modes that might be relevant in this investigation, such as catastrophic failure, memory loss, noise, cross-talk, improper gain, and instability.

The failure mechanisms for the above modes could include chemical attack, creep, aging, overpressure (or underpressure), surface erosion, thermal distortion, channel corrosion, stress corrosion fatigue, film buildup, and fluid contamination. A review of these modes and mechanisms allows one to classify the dominant mechanism into three groups.

1. Ambient effects
2. Transport fluid effects
3. Geometric effects.

In devising a program that would meaningfully evaluate these effects on fluid amplifier failure, it was deemed necessary to make this test not only sensitive to the main effects of these mechanisms, but also to their sequence of occurrence. This could best be achieved by designing a statistical test* using pressure, temperature, and contamination as the three factors influencing the six stacks of elements, each stack consisting of fifteen digital fluid amplifiers, previously referred to as shift registers.

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*For discussion of statistical testing, see National Bureau of Standards Handbook No. 91, "Experimental Statistics," August 1963.

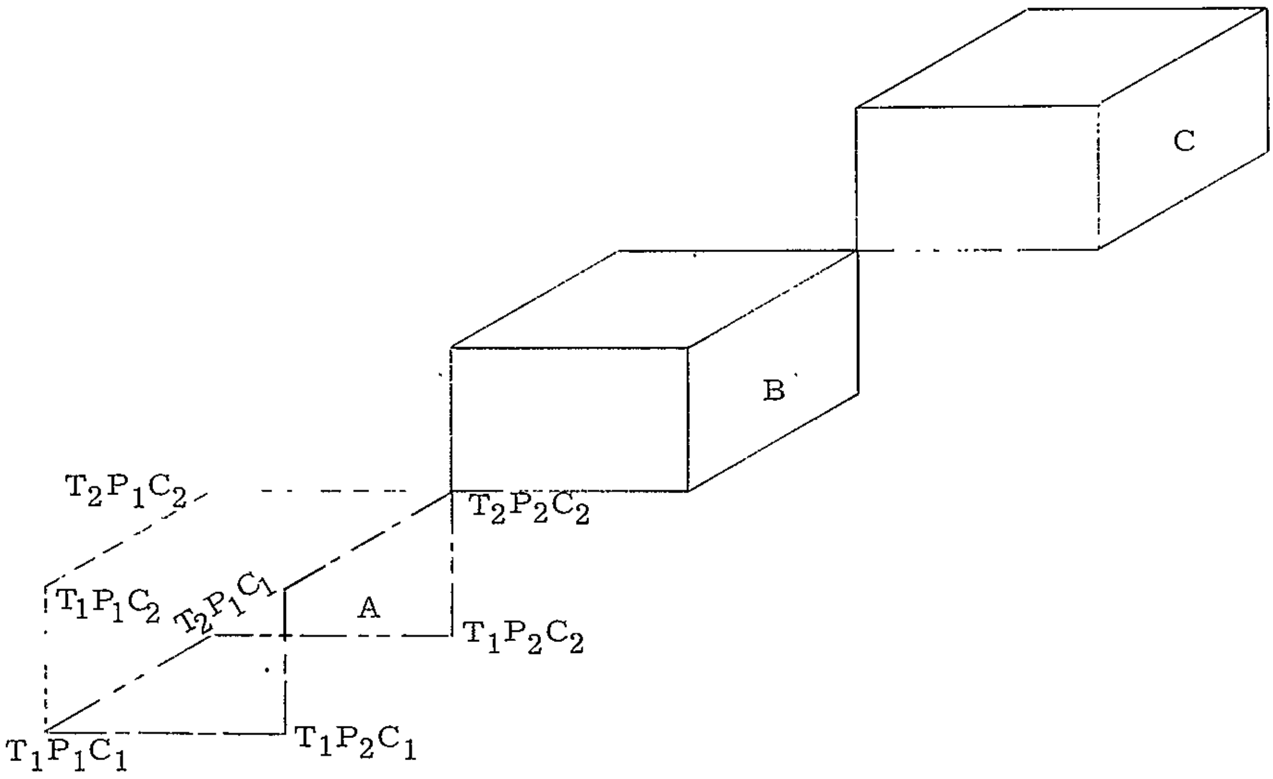

Figure 1. Statistical Test Profile

Figure 1 illustrates the statistical test profile that was followed. All six shift registers are initially tested under T_1, P_1, C_1 conditions. Upon completion of the test for a specified number of hours, the registers are divided into three groups of two each and are tested under the following conditions:

Two shift registers at T_2, P_1, C_1 followed by T_2, P_2, C_1

Two registers tested at T_1, P_2, C_1 followed by T_1, P_2, C_2

Two registers to be tested at T_1, P_1, C_2 followed by T_2, P_1, C_2

Upon completion of this test path, all six registers were again tested at T_2, P_2, C_2. Additional stress levels for these factors can be obtained by progressively testing within Blocks B and C, etc., in a manner similar to that followed in Block A until all registers have been tested at T_3, P_3, C_3, and so on. This latter graduated test (Blocks B and C) however, was beyond the scope of this program.

Section 4

DISCUSSION

4.1 TEST APPROACH

The serial shift register was selected as the most convenient test device because:

1. It is a digital device and failures are easily defined and identified
2. By recirculating information initially set into a register, the failures become "self-recording", i. e., failure of any one fluid element at any time will change the stored information
3. Instrumentation is relatively simple. Because of failure self-recording the instrumentation is not subjected to long test times; it is used only during periodic monitoring

The registers were a five-stage device (Figure 2&3) which provided five-bit serial word storage capacity. Bit storage was provided by a fluid amplifier flip-flop and digital amplifiers were used to gate information from a given flip-flop to the succeeding flip-flop. Thus, application of a clock pulse to the register advanced the stored information by one bit. Since the register output was connected back to the input (similar to a ring counter), the application of five clock pulses brought the initially stored information back to the same position. Each digital element used in the six-shift registers was selected via the procedure discussed in Appendix C. The clock pulses were generated by a motor-driven slotted disc at a rate of 120 pulses per second. A view of the assembled test rig is shown in Figure 4.

A particular serial binary number preset in the register was observed by means of a pressure transducer attached at one of the feedback lines (register output to input). An oscilloscope was used to observe the transducer signal; a positive-pressure pulse arbitrarily was assigned the value "1" and correspondingly negative-pressure pulses became "0" as shown in Figure 5. The front or "leading edge" of the five-bit number was identified in the pulse train appearing on the oscilloscope by proper selection of the initially set numbers. For example, if the number 11010 is preset into the register, the two most significant digits are identified by the adjacent "1"s (Figure 5). It is conceivable that several failures could occur such that one set of adjacent "1"s could appear in other than the preset arrangement. It was concluded that the likelihood of such occurrences would be very small. Future work with the setup will include a marker pulse to avoid this assumption.

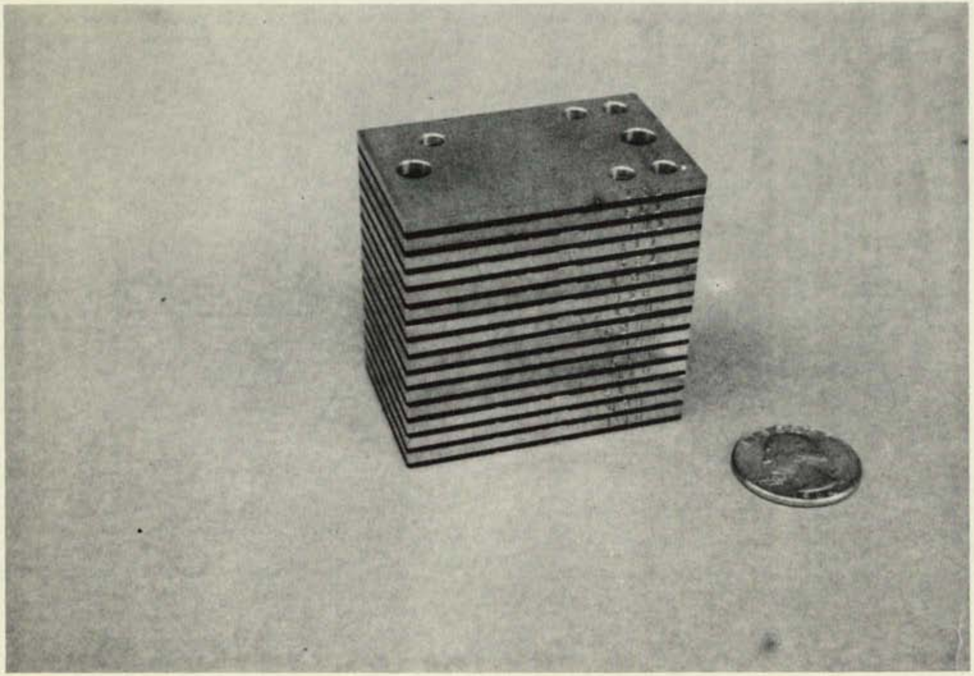

Figure 2. View of Shift Register

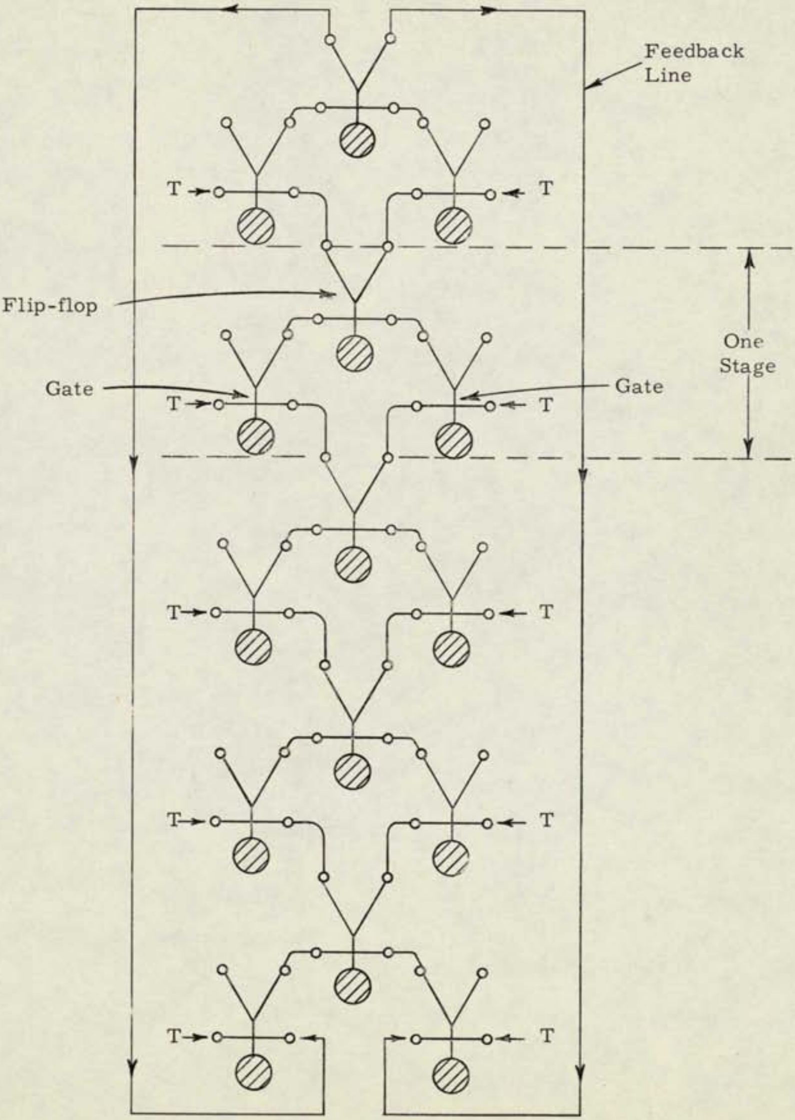

Figure 3. 5-Bit Shift Register

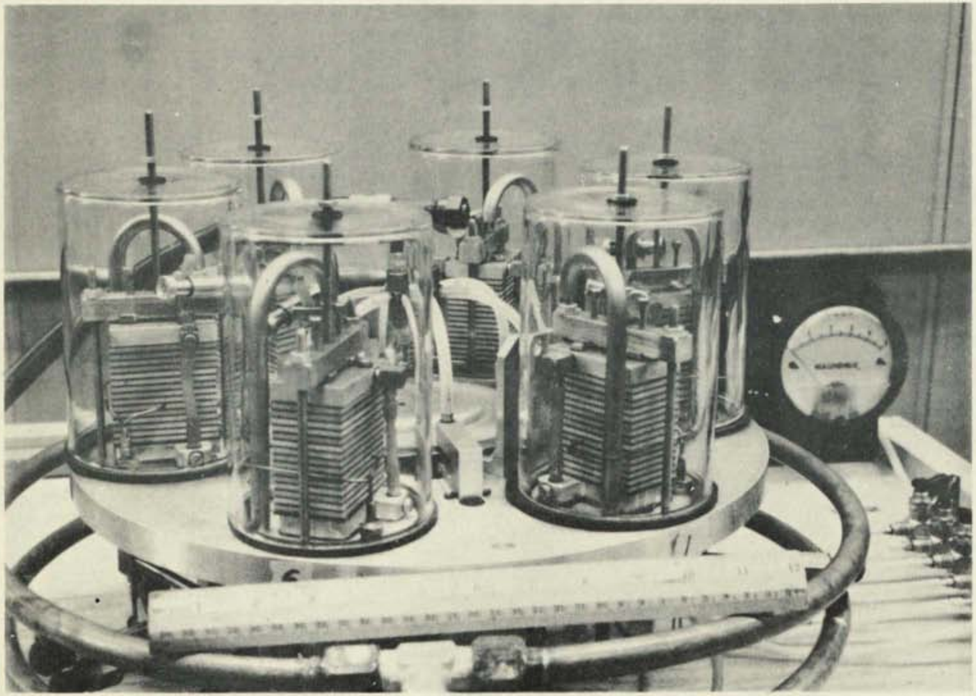

Figure 4. Test Apparatus

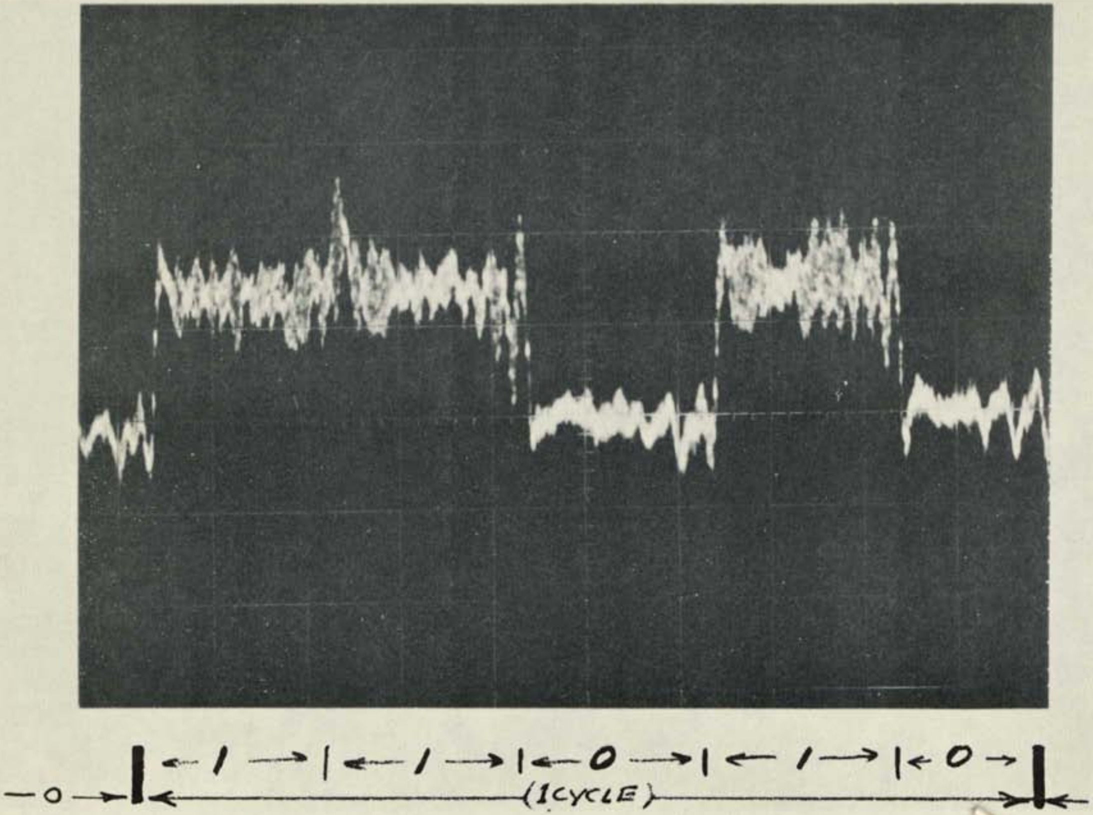

Figure 5. Readout Signal Characteristic

The test setup also included a line pressure recorder and an indicator to detect any power failures that may have occurred between monitoring periods. Without this instrumentation loss of line pressure or electrical power will cause the registers to drop information. Hence, such losses could be mistaken for register failures.

The testing was carried out in three phases. The Phase I test was carried out with all six registers operated at design conditions. This test duration was relatively long (approximately 1872 hours) to obtain large amounts of data, to more accurately establish failure rates at unstressed conditions, and to learn if preferential failure modes occur (e. g. , characteristics of a particular number or register). During this test, the supply pressures to the registers were at the design values (1. 5 and 2. 0 psig to the flip-flops and the gates respectively), the temperature of the ambient and supply gas was at room temperature, and the registers were operated in a relatively clean environment. The setup was operated 24 hours per day and monitored once per day.

In the Phase II testing, the selection of stress levels was dictated by the register design and the fabrication materials. It was concluded that the most likely change in supply pressure would be a pressure drop (e. g. , caused by line or fitting leaks, or supply pump deterioration). By test it was established that the registers would operate as low as 50 percent of the design value for supply pressure. The value of 25 percent supply pressure drop was selected as the stress level for pressure change. This pressure change was used for the flip-flop, the gates, and the input clock pulses.

The temperature stress selected was an increase in supply air temperature from room temperature to 160° F. This limitation occurred because of the photo-etched plastic fabricating material used for the fluid amplifier elements (program limitation did not permit use of higher temperature materials).

The contamination stress was applied by placing the register in a small bell-jar with a measured quantity (10 ml) of Arizona road dust (Mil-Spec) to simulate a typical dusty field environment. The dust was "stirred" daily with small air jets to produce a cloud of contamination adjacent to the register. Vents from the fluid amplifier elements communicated with the dust environment and thus the dust was injested by the elements at locations where aspiration from the environment occurred; Figure 6 shows a register after operating in the dust environment. Contamination was not added directly to the supply air.

The Phase II testing sequence involved operating a pair of registers for about 400 hours under successive stress conditions as shown in Table 2.

During the course of the testing in Phases I and II, it became evident that the failures apparently were nonrandom. In particular, the failure rate of a given register seemed to be a function of the particular digital number

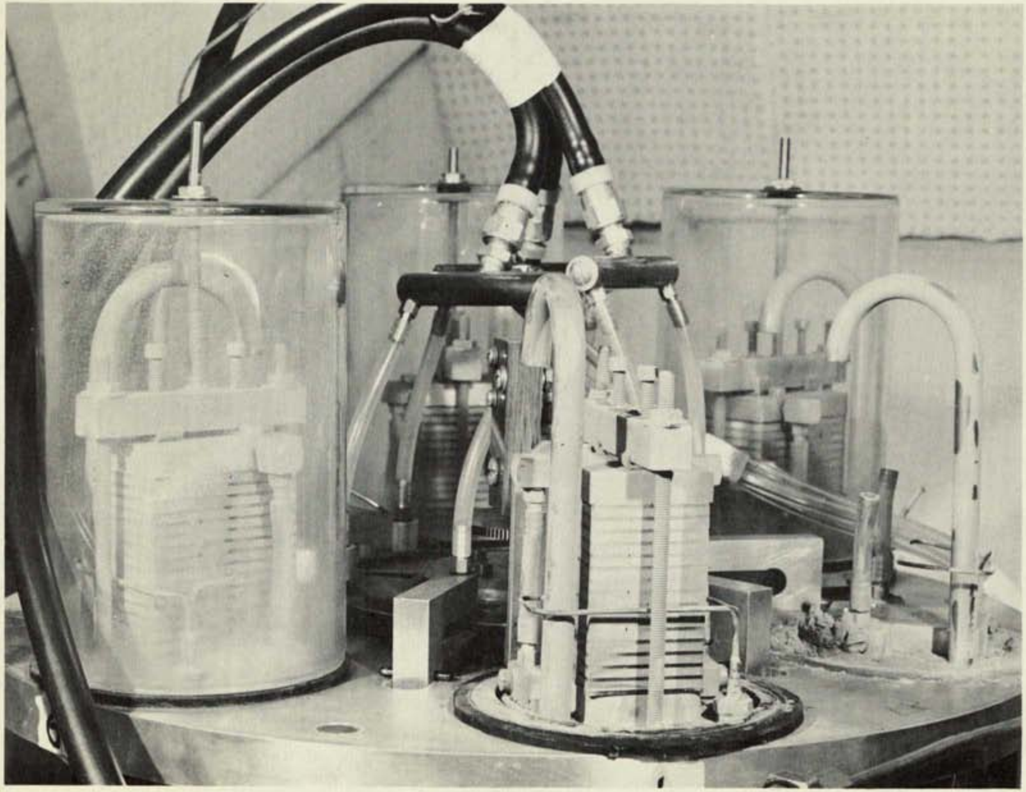

Figure 6. Shift Register After Operation in a Dusty Environment

PHASE II TEST PROCEDURE

	Registers 1 and 2	Registers 3 and 6	Registers 4 and 5
Test 1	P	T	C
Test 2	C	P	T
Test 3	T	C	P

C = contamination
P = supply pressure change
T = supply temperature change

initially set into it. As pointed out earlier, no marker was used to identify the leading edge of the five digits. The leading edge was identified by clustering units towards it. For example, a 10100 initially set in later would appear on the oscilloscope as a train of pulses with two "1"s separated by a "0". The scope then was synchronized so that the number would appear as a 10100. The lack of a marker signal limited the choice of binary numbers to be set in. For example, 10100 could not be distinguished from 01010, 00101, or 01001. The numbers used for presetting the registers during the Phase I and Phase II testing were as follows:

10100
11010
11110
10000

The numbers 11111, 11100, 11000, and 00000 were not used.

The Phase III testing was carried out at design conditions to determine if any permanent damage had occurred as a result of the stressed tests. Conforming to the procedure at the start of the design condition testing, the registers were monitored at one hour intervals when the test started. During this test phase, all possible number combinations without a time marker were used (10100, 11010, 11110, 10000, 11111, 00000, 11100, and 11000) since the failures seemed to be nonrandom, i. e., a function of the preset number. In addition, during this test each register was set to the same number for about one day for each of the eight numbers and then repeated completely. Thus, Phase III involved a total of about 16 days of testing. Whenever a failure was noted, the shift register was set back to the value for that day.

The data obtained in this manner provided the necessary information to determine if the nonrandom failures were caused by differences in shift registers or if the registers behaved differently with different preset numbers or both. Use of a marker to positively identify the number's leading edge would provide the greatest number of presettings (32); thus, the most information on nonrandom failure tendencies. Future tests should include the use of such a marker. Following the three phases of testing, two registers were carefully disassembled to determine if any evidence of a deficiency could be observed which could cause malfunctioning. The findings are presented at the end of this report.

4.2 NATURE OF THE TEST DATA

The experimental results have been summarized in Appendix A. Tables A-1 through A-6 show the detailed failure patterns and the number of elapsed days between the setting of the number in the register and the determination that it has been lost for Phases I, II, and III. Also indicated is where a failure did not occur previous to the setting being changed.

The results have been summarized according to the set-in value, shift register, environmental conditions, and test phase in Table A-7. Finally, error movements (failure from a particular set-up value to a particular read-out value) are summarized in Table A-8. Taken as a whole:

1. The data suggests a higher failure rate under increased temperature on some shift registers, but not on others, with no clearcut evidence that pressure or contamination levels experienced lead to any change in mean-time-to-failure. In evidence, note that the aggregate failure report at each of the test conditions was (see Table 3)

Table 3

FAILURE SUMMARY

Condition	Number of Shift Register Test Days	Number of Failures	Mean Number of Days to Failure
Standard - Phase I	486	51	9.5
Pressure Stress	108	17	6.4
Contamination	81	9	9.0
Temperature Stress	105	31	3.4

Whereas, by shift register the failure distribution was:

Shift Register Number	1	2	3	4	5	6
Failures - Phase I	0	8	2	2	10	21
Failures - Phase II	8	16	8	0	33	0
Failures - Phase III*	2	0	0	0	51	0

---

*The results are not comparable between test Phase III and test Phases I and II due to the difference in number of test days and inspection times. For example, if inspections in Phase III would have been on a daily rather than an hourly basis, 8 rather than 51 failures would have been recorded. The results are, however, comparable between shift registers.

The above tables make clear the very large differences in performance between the shift registers*. Note also that the relative performance of the shift registers was not consistent over the two phases. Near the end of Phase I, Shift Register No. 4 which to that point had a low failure rate was switched in location in the test apparatus with Shift Register No. 6 which up to that point had a high failure rate. Subsequently, no failures occurred on Shift Register No. 6 in eight further days of Phase I testing and throughout Phases II and III. Shift Register No. 4 also had no failures during Phases II and III and only one failure during eight days at its new position in Phase I. Comparison of the results of initial testing at standard conditions (Phase I) and final testing at standard conditions (Phase III) indicated that Shift Register No. 6 performed appreciably better in the subsequent testing than it did in Phase I, Shift Register No. 5 seemed to do somewhat worse, and the remainder did approximately the same. .

The reaction to change in test condition also varied among the shift registers. As indicated, Shift Registers No. 4 and No. 6 performed without failure at each of the three changed environments. In contrast, however, Shift Register No. 5 failed almost equally readily at each condition. This shift register showed about the same failure rate during an initial 14-day period of normal testing (no variation in test condition) during Phase II as it did under environmental change. Consequently, the high failure rate on this shift register during Phase II cannot necessarily be attributed to the change in testing condition.

On Shift Register No. 1, all eight Phase II failures took place during change in temperature with no failures under pressure and contamination change. On Shift Register No. 3, six of the eight failures in Phase II took place under temperature change and the remaining two took place under contamination. There were no failures on Shift Register No. 3 under pressure change. Finally, on Shift Register No. 2, nine and seven failures respectively took place under changed temperature and pressure with no failures under contamination.

2. There is no conclusive evidence to suggest a residual effect of a previous stress condition.

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*Shift Register No. 1 ran 114 consecutive days before its first failure occurred (See Table A-1, Appendix A).

The two shift registers with a predominant number of failures during accelerated temperature testing were Registers No. 1 and No. 3. No information can be gathered concerning residual effects by examining the results on Shift Register No. 1 during Phase II, since the increased temperature testing on this shift register was conducted last (after the pressure and contamination change). However, two failures did take place in Phase III.

Shift Register No. 3 does provide an evaluation of residual effects, since the increased temperature testing on this shift register was conducted as the first environmental change. It was found that immediately subsequent to increased temperature testing there were no failures in 15 days of testing at changed temperature and only four failures in the 16 days following days with contamination. Furthermore, there were no failures on this shift register in Phase III. Thus, the data on Shift Register No. 3 suggests that the failure pattern observed during increased temperature testing does not hold over in subsequent tests after the temperature has been returned to normal.

3. Various nonrandom patterns asserted themselves. The specific patterns noted were:

a. Seventy-seven of the Phase I and Phase II failures were simple in that only one of the five binary numbers was involved in the failure. The remaining 31 failures involved two or more binary numbers. The exact nature of these failures (i. e. , the specific binary bits involved) can be gathered from Tables A-1 through A-6 (and are also discussed further below.

b. During Phase I, failure rates for a particular shift register were found to vary greatly from one set-up value to the next. For example, for Shift Register No. 5, there were two failures in 20 days of operation for a set-up value of 10000, one failure in 45 days of operation for a set-up value of 10100, and seven failures in nine days of operation for a set-up value of 11110. The corresponding results for the other five shift registers are shown in Tables A-1 through A-4 and Table A-6. This pattern was not evident in Phase II.

Phase III was designed so as to permit clear-cut evaluation of the differences in failure rate for different set-in values. The results on Shift Register No. 5 in this phase confirmed the previous findings that the failure rate depended upon the set-in value of the shift register, as demonstrated by Table 4.

Table 4

SHIFT REGISTER #5 PHASE III FAILURE DETAIL

Set-in Value	First Day Number of Failures	 Number of Readings	Second Day Number of Failures	 Number of Readings
00000	0	7	0	8
11111	0	9	0	8
11110	0	0	0	0
11100	2	6	3	9
11000	9	9	8	8
10000	9	9	8	8
11010	0	8	0	8
10100	6	7	6	6

It is particularly noteworthy that the differences in results between set-in values repeated very well between the two days at which each set-in value was tested. This repeatability, however, does not carry over when the results on Shift Register No. 5 on the additional tests are compared with those previously noted for Phase I. For example:

> The set-in value 10100 yielded 12 failures in two days of additional testing, but only one failure in 45 days of testing during Phase I (this value was not used for set-in on Shift Register No. 5 during Phase II).
>
> The Set-in value 10000 yielded 17 failures in two days of additional tests, but only two failures in 20 days of testing during Phase I (this set-in value also yielded a substantial number of failures in Phase II).

Certain failure patterns are much more prominent than others. For example, 15 of the 26 simple failures during Phase I were of the type 11110 to 11100. The specific changes in binary values which were involved in each of the 43 failures of Phase I and the 65 failures of Phase II are summarized in Table A-8. The probabilities of each simple failure, given a set-up in a particular location are also indicated on this table. For example, given the set-up 11110, the following simple failures are possible:

Change to 11010 (two chances out of five)
Change to 11100 (two chances out of five)
Change to 11111 (one chance out of five)

Thus, the most likely pattern of the 16 failures of Phase I, assuming random failure, would be as follows:

Change to 11010 - six or seven failures
Change to 11100 - six or seven failures
Change to 11111 - three or four failures

It is seen from Table A-8 that the actual results showed zero failures, 15 failures and one failure respectively in the above three categories. Thus, one would suspect that the failure patterns are nonrandom. This can be confirmed by comparing the actual results with the expected results using a statistical chi-square contingency test. *

Moreover, the failure patterns observed in Phase II differed markedly from those in Phase I as illustrated by the following tabulation of simple failures based on a set-up value of 11010:

	Phase I	Phase II
Change to 10100	0 Failures	15 Failures
Change to 11000	4 Failures	0 Failures
Change to 11110	0 Failures	2 Failures

d. Failure susceptibility for a particular shift register using a specified set-up value also tended to vary over the period of the test. For example, the failure sequence during Phase I on Shift Register No. 6 with regard to the set-up value 11110 was:

Failure after one day using set-up value 11110

Failure after three days using set-up value 11110

Failure after one day using set-up value 11110

Failure after one day using set-up value 11110

Twenty-two days using other set-up values**

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*Davies, O. L., Statistical Methods in Research and Production, Chapter 9, Hafner Publishing Company, 1957, or Dixon, W. J. and Massey, F. R., Introduction to Statistical Analysis, Chapter 13, McGraw-Hill Book Company, 1951.

**Results at other set-up values are not pertinent to this analysis since it has been previously shown that different failure rates are obtained for different set-up values.

Failure after one day using set-up value 11110

Failure after zero days

One day using other set-up values*

No failure for 17 days using set-up value 11110

Eight days using other set-up values

Failure after six days using set-up value 11110

Failure after four days

No failure after eight days using set-up value 11110

It is evident that failures occurred more frequently for this particular set-up shift register combination near the beginning of the testing phase than near the end. Other combinations can be studied by examining Tables A-1 through A-6.

4. Confidence intervals on mean-time-to-failure were not calculated, although this could easily have been done by standard techniques. It was felt that such a calculation would be misleading because of:

a. The differences between shift registers; thus, the confidence figure would vary from one shift register to the next. The same difference also clouds the evaluation of the significance of decreased mean-time-between-failures under stressed conditions.

b. The nonrandom nature of the data, which leads to variations in reliability according to input value and time.

c. The possibility that some failures during Phases I and II could have occurred long before the actual read-out time (readings were taken on a daily basis and not on week ends), thus leading to over-optimistic estimates.

It must be emphasized that while examining the above results, one must keep in mind that they are based on a preliminary study involving six shift registers only. Additional information need be obtained to confirm some of the initial trends that have been noted to date.

---

*Results at other set-up values are not pertinent to this analysis since it has been previously shown that different failure rates are obtained for different set-up values.

4.3 INSPECTION RESULTS

After completion of the Phases I, II, and III testing, two registers were disassembled to learn if causes for failure could be detected. Shift Register No. 5 was selected for disassembly since at the completion of the Phase III testing (standard conditions) it had very high failure rates (at least one hour). In addition, a register with low failure rates (Shift Register No. 2) was disassembled to provide a basis for comparison.

The appearance of the individual register elements was excellent. The only visual differences between their condition at initial assembly and at this teardown were three types of internal contamination:

1. Small amounts of Arizona road dust "plated out" on vent channels near their termination to the ambient.
2. Light coating of oil in the channels; oil condensation occurred elsewhere in the test set-up indicating oil vapor in the air supply.
3. A thin black varnish-like deposit in the interaction region of the elements. The deposits appeared most concentrated at high velocity points.

Closer inspection and comparison of the elements from the operating and the failing registers revealed that the epoxy bonding used to seal covers on the element cutouts may have failed. The evidence of failure was that the oil film in the various element channels extended on to some surfaces (cover and element cutout) that were supposed to be bonded before disassembly. The only explanation for the oil film appearing on the supposedly bonded surfaces is that separation of the bonded joint occurred and allowed leakage to occur. Since the failure rates increased when the temperature was increased it was concluded that the bonding failures occurred because of overstressing from differential expansion of the fabricating materials. Inspection of the covers and element cutouts of the properly operating register revealed no oil film on the bonded surfaces; this information provided further verification that bonded joint failure occurred in Shift Register No. 5.

Further testing, which is beyond the scope of the present program, could be carried out to determine more conclusively the physics of the failures. For example, the failing register and a properly operating one could be interchanged on the test set-up to verify that the failures were internal to the registers and not in the test equipment. In addition, each element from each register could be retested to determine if any significant changes of element performance had occurred. Specifically, the element acceptance tests could be rerun and the curves could be compared to the elements in the new condition. This test would reveal if any degradation of the element occurred because of erosion or other causes. Future work should include careful consideration of the plans for teardown and inspection, since corrective action for failures will be meaningful only if the exact causes for failures can be determined.

Appendix A

TEST DATA

Table A-1

SHIFT REGISTER NO. 1 RESULTS

Digit Order Set Value	Approximate Number of days At Set Value	Failed to Digit Reset	No Failure Digit Reset
PHASE I (NO STRESS)			
11010	1		x
11110	3		x
10100	1		x
10000	3		x
11110	3		x
10100	22		x
11010	21		x
10000	24		x
PHASE II (PRESSURE STRESS)			
11010	12		x
10100	10		x
PHASE II (CONTAMINATION)			
10100	14		x
PHASE II (TEMPERATURE STRESS)			
11010	0-1	10100	
11010	0-2	10100	
11010	0-1	10100	
11010	0-3	10100	
11010	2-4	10100	
11010	0-4	10100	
11010	0-1	10100	
11010	0-1	10100	
11010	1		

Table A-1 Cont.

PHASE III (NO STRESS)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x
00000	9		x
11111	9		x
11110	9		x
11100	6	11000	
11100	2		x
11000	9		x
10000	3	00000	
10000	5		x
11010	9		x
10100	9		x

Table A-2

SHIFT REGISTER NO. 2 RESULTS

PHASE I (NO STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
11110	1	11100	
11100	0		x
10100	2		x
11110	0	11100	
11010	4	11000	
11010	1		x
10000	13	11000	
11010	9		x
11110	1	11100	
11110	3	11100	
11110	7	11100	
11110	10		x
10100	21	11111	
10100	4		x

PHASE II (PRESSURE STRESS)

10100	0-7	11010	
10100	0-2	11010	
10100	0-1	11010	
10100	0-3	11010	
10100	0-1	11010	
10100	0-1	11010	
10100	1-2	11010	
10100	5		x

PHASE II (CONTAMINATION)

10100	15		x

PHASE II (TEMPERATURE STRESS)

11010	0-1	10100	
10000	0-2	11000	
11110	0-1	11000	

Table A-2 Cont.

PHASE II (TEMPERATURE STRESS) (continued)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
11110	0-3	11000	
11110	0-2	11000	
11010	0-2	10100	
11010	3-4	10100	
11010	0-1	10100	
10000	0-1	11000	

PHASE III (NO STRESS)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x

Table A-3

SHIFT REGISTER NO. 3 RESULTS

PHASE I (NO STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
10000	3		x
11100	2		x
11110	26		x
10000	20		x
11010	19	11111	
11010	2	11111	
11010	4		x

PHASE II (TEMPERATURE STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
11010	0-1	10100	
11010	0	10000	
10100	*		
11010	*		
11110	*		
10000	6-8	00000	
10100	1-4	10000	
11010	0-1	10000	
10100	0-1	10000	
10100	2		x
10000	*		
11000	*		
10000	1		x

PHASE II (PRESSURE STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
10000	15		x

PHASE II (CONTAMINATION)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
10000	8		x
11010	0-2	10100	
11010	0-3	10100	
11010	3		

*Unable to Set Digit Order

Table A-3 Cont.

PHASE III (NO STRESS)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
10000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x

Table A-4

SHIFT REGISTER NO. 4 RESULTS

PHASE I (NO STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
11100	1	00000	
11010	3		x
10100	5		x
11010	22		x
11110	20		x
10100	18		x

Shift Register Moved to Position Six

10100	3	11000	
10100	5		x
11010	14		x

PHASE II* (CONTAMINATION)

11010	8		x

PHASE II* (TEMPERATURE STRESS)

10100	14		x

PHASE II*(PRESSURE STRESS)

10000	16		x

PHASE III (NO STRESS)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x

*Shift Register in Position Six

Table A-4 Cont.

PHASE III (NO STRESS) (continued)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
11010	9		x
10100	9		x
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x

Table A-5

SHIFT REGISTER NO. 5 RESULTS

PHASE I (NO STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
11100	1		x
10100	2		x
11010	1		x
10100	5		x
10000	11	11100	
10000	2	11000	
11110	1	11100	
10000	7		x
10100	21		x
11110	1	00000	
11110	3	11100	
11110	1	11100	
11110	1	11100	
11110	1	11111	
11110	1	11100	
10100	10	11010	
10100	7		x
10000	0-1	11100	
10000	0-1	11110	
10000	0-1	11110	
10000	0-3	00000	
10000	0-1	00000	
10000	0-2	11110	
10000	0-2	00000	
10000	0-3	11110	

PHASE II (CONTAMINATION)

11110	1-2	11000	
11110	0-1	11100	
11110	0-1	11100	
11110	0-3	11111	
11110	0-1	10000	
11110	0-1	00000	
11110	0-1	00000	

Table A-5 cont.

PHASE II (TEMPERATURE STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
11110	could not hold set value		
10000	0-1	00000	
10000	1-2	00000	
10000	0-1	00000	
10000	1-4	00000	
10000	0-1	00000	
10000	0-1	00000	
10000	0-2	00000	
10000	0-3	00000	

PHASE II (PRESSURE STRESS)

10000	0	00000	
10000	0-1	00000	
10000	2-3	00000	
10000	0-3	00000	
10000	0-2	00000	
10000	0-2	00000	
10000	0-3	00000	
10000	0-1	00000	
10000	0-1	00000	
10000	0-1	00000	

PHASE III (NO STRESS)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
00000	9		x
11111	9		x
11110	9		x
11100	5	11110	
11000	1*[1]	11100	
11000	1*[2]	11110	
10000	1	11000	
10000	1*[3]	11100	
10000	1*[4]	11000	
10000	1	11100	
10000	1	00000	
11010	9		x

Table A-5 Cont.

PHASE III (NO STRESS) (continued)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
10100	1*[5]	11010	
00000	9		x
11111	9		x
11110	9		x
11100	2	11110	
11100	5	11110	
11100	1	11000	
11000	1	11100	
11000	1	11110	
11000	1*[6]	11100	
11000	1*[7]	11110	
10000	1	11000	
10000	1	11100	
10000	1*[8]	11110	
10000	1	11100	
11010	9		x
10100	4	11010	
10100	1	11100	
10100	1*[9]	11010	

*[1] - Repeated six times at once per hour (hourly readings)
*[2] - Repeated three times at once per hour (hourly readings)
*[3] - Repeated three times at once per hour (hourly readings)
*[4] - Repeated four times at once per hour (hourly readings)
*[5] - Repeated nine times at once per hour (hourly readings)
*[6] - Repeated four times at once per hour (hourly readings)
*[7] - Repeated two times at once per hour (hourly readings)
*[8] - Repeated five times at once per hour (hourly readings)
*[9] - Repeated four times at once per hour (hourly readings)

Table A-6

SHIFT REGISTER NO. 6 RESULTS

PHASE I (NO STRESS)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
10100	1	11000	
10000	1	11000	
11110	1	11100	
11110	3	10000	
11110	1	11100	
11110	1	11000	
11010	1	11000	
10100	6	10000	
11010	4	11000	
11010	1	11000	
10100	10		x
11110	1	11100	
11110	0	11100	
10000	1	11000	
11110	17		x
10000	1	11100	
10000	3	11100	
10000	1	11110	
10000	1	11111	
10000	1	11111	
10000	1	11100	
11110	6	11100	
11110	4	00000	

Shift Register Moved to Position 4

11110	8		x

PHASE II* (TEMPERATURE STRESS)

10100	23		x

PHASE II* (PRESSURE STRESS)

10100	18		x

Table A-6 Cont.

PHASE II* (CONTAMINATION)

Digit Order Set Value	Approximate Number of Days At Set Value	Failed to Digit Reset	No Failure Digit Reset
10100	16		

*Shift Register in Position Four

PHASE III (NO STRESS)

Digit Order Set Value	Approximate Number of Hours At Set Value	Failed to Digit Reset	No Failure Digit Reset
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x
00000	9		x
11111	9		x
11110	9		x
11100	9		x
11000	9		x
10000	9		x
11010	9		x
10100	9		x

Table A-7

SUMMARY OF TEST RESULTS

Shift Register Number	Phase	Condition	Setting Sequence	Set In Value																	
				10000			10100			11010			11110			11100			Total		
				D	F	M	D	F	M	D	F	M	D	F	M	D	F	M	D	F	M
1	I			27	0	∞	23	0	∞	22	0	∞	6	0	∞				78	0	∞
	II	N	1																		
	II	P	2				10	0	∞	12	0	∞							22	0	∞
	II	C	3				14	0	∞										14	0	∞
	II	T	4							18	8	2.3							18	8	2.3
2	I			13	1	13.0	27	1	27.0	14	1	14.0	22	5	4.4				76	8	9.5
	II	N	1																		
	II	P	2				22	7	3.1										22	7	3.1
	II	C	3				15	0	∞										15	0	∞
	II	T	4	3	2	1.5				8	4	2.0	6	3	2.0				17	9	1.9
3	I			23	0	∞				25	2	12.5	26	0	∞	2	0	∞	76	2	38.0
	II	N	1																		
	II	P	3	15	0	∞													15	0	∞
	II	C	4	8	0	∞				8	2	4.0							16	2	8.0
	II	T	2	9	1*	9.0*	7	2*	3.5*	2	3*	7*		*	*		*	*	18	6*	3.0
4	I	A					23	0	∞	25	0	∞	20	0	∞	1	1	1.0	69	1	69.0
	I	B					8	1	8.0										8	1	8.0
	II	N	1							14	0	∞							14	0	∞
	II	P	4	16	0	∞													16	0	∞
	II	C	2							8	0	∞							8	0	∞
	II	T	3				14	0	∞										14	0	∞
5	I			20	2	10.0	45	1	45.0	1	0	∞	9	7	1.3	1	0	∞	76	10	7.6
	II	N	1	14	8	1.8													14	8	1.8
	II	P	4	17	10	1.7													17	10	1.7
	II	C	2										10	7	1.4				10	7	1.4
	II	T	3	15	8	1.9								*	*				15	8	1.9
6	I	A		10	8	1.3	17	2	8.5	6	3	2.0	34	8	4.3				67	21	3.2
	I	B											8	0	∞				8	0	∞
	II	N	1																		
	II	P	3				18	0	∞										18	0	∞
	II	C	4				16	0	∞										16	0	∞
	II	T	2				23	0	∞										23	0	∞
Total	I		-	93	11	8.5	143	5	28.6	93	6	15.5	125	20	6.3	4	1	4.0	458	43	10.7
	II	N		14	8	1.8				14	0	∞							28	8	3.5
	II	P		48	10	4.8	48	7	6.9	12	0	∞							108	17	6.4
	II	C		8	0	∞	47	0	∞	16	2	8.0	10	7	1.4				81	9	9.0
	II	T		27	11*	2.5*	44	2*	*	28	15*	1.9*	6	3*	2.0*		*	*	105	31*	3.4

Schedule of Conditions:

	Temperature	Pressure	Contamination
N	25°C	1.5 -2.0 psi	None
P	25°C	1.25-1.5 psi	None, or added - not stirred
C	25°C	1.5 -2.0 psi	Added and stirred
T	70°C	1.5 -2.0 psi	None, or added - not stirred

Key

D - total number of days

F - number of failures

M - mean number of days between failures

* Indicates value could not be held in shift register

NOTE:

Phase III results not included. Different reading frequency for a shorter period of time does not lend itself to establishing a mean-time-to-failure.

FOOTNOTE:

Condition A: Shift Registers 4 and 6 in Position 4 and 6 Respectively

Condition B: Shift Registers 4 and 6 in Position 6 and 4 Respectively

Table A-8

SUMMARY OF ERROR MOVEMENTS

	Set-up Value																							
	10000				10100				11010				11110				11100				11000			
Probability of Occurrence				P				P				P				P				P				P
Phase	I	II	III		I	II	III		I	II	III		I	II	III		I	II	III		I	II	III	
Read Out Value																								
00000	0	22	1	1/5	0	0	0		0	0	0		2*	2	0				0				0	
10000					0	0	0	2/5	0	2	0		1*	1	0				0				0	
10100	0	2	0	2/5					0	15	0	2/5	0	0	0				0				0	
11000	4	2	5	2/5	2*	0	0		4	0	0	1/5	1*	4	0				2	2/5				
11010	0	0	0		1	7	10	2/5					0	0	0	2/5			0				0	
11100	4*	1	6*		0	0	1	1/5	0	0	0		15	2	0	2/5							11	2/5
11110	1*	4	5*		0	0	0		0	0	0	2/5							3	2/5			6*	
11111	2*	0	0		1*	0	0		2*	0	0		1*	1	0	1/5			0				0	

* Indicates complex failures, i. e., more than one bit change. All other failures are simple (one bit change)

NOTE

1. The probability of occurrence is calculated assuming that all possible simple failures are equally likely.
2. Phase I and Phase II readings were taken daily whereas Phase III readings were taken hourly.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☐
Digital ☐
Counter ☐
Hybrid ☒

Environmental Information:

1. Test Duration Prior to Failure (operational hours):
   100 hours
2. Test Conditions at Failure:
   a. Cyclic Parameter
      Pressure x Temperature
      Peak-to-peak Amplitude: 4 psi
      Frequency: 90 - 200 cps
   b. Steady-state Parameter:

	P_S P_{C_L} P_{C_R} P_V P_{R_L} P_{R_R}	T_F T_{Amb}
(psig)	≈ 10	70 (°F)

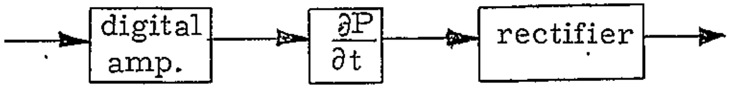
3. Prior History:
   No failures. Slight periodic gain changes. No recalibration requested.
4. Corrective Action:
   Recalibrated circuit by adjusting supply pressure
5. Circuit Description:
   (One sentence maximum. Attach diagram)
   Frequency to analog converter

Failure	Probable Cause													
	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedance Match	Vent Pressure	Mfg. Control	Other:
Memory Loss														
Null Shift														
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change		x												
Frequency Response														
Instability														
Mechanical														
Other:														

Evidence of Probable Cause:

Circuit inadvertantly calibrated with chipin nozzle. Chip loosened in shipment causing reduction in supply pressures from 9.3 to 8.0 psig.

Date: 9/28/65 Signed: D. L. R.



FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☐
Digital ☒
Counter ☐
Hybrid ☐

Environmental Information:

1. Test Duration Prior to Failure (operational hours):
   8 hours
2. Test Conditions at Failure:
   a. Cyclic Parameter
   Pressure x Temperature
   Peak-to-peak Amplitude: 13 psig
   Frequency: 1 cpm
   b. Steady-state Parameter:

$P_S\ P_{C_L}\ P_{C_R}\ P_V\ P_{R_L}\ P_{R_R}\ T_F\ T_{Amb}$

(psig) -10 to +25 0 to -13 70°F

3. Prior History:
4. Corrective Action:
   Removed contaminant
5. Circuit Description:
   (One sentence maximum. Attach diagram)
   1 SR6C amplifier used as a barometric switch

Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:
Memory Loss						X								
Null Shift														
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change														
Frequency Response														
Instability														
Mechanical														

(Columns from Leaks to Other: are headed "Probable Cause".)

Other:

Evidence of Probable Cause:
Small piece of rubber in nozzle

Date: 9/65 Signed: D. L. R.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒
Digital ☐
Counter ☐

Environmental Information:
150 hours

1. **Test Duration Prior to Failure** (operational hours):

2. **Test Conditions at Failure:**
   a. Cyclic Parameter
      Pressure x Temperature
      Peak-to-peak Amplitude: 1.5 psi (input)
      Frequency: 150 cps
   b. Steady-state Parameter:

	P_S	P_{C_L}	P_{C_R}	P_V	P_{R_L}	P_{R_R}	T_F	T_{Amb}
(psig)								70°F

3. **Prior History:**
   No problems

4. **Corrective Action:**
   The solution was the elimination of the sticky tape used as a sealer.

5. **Circuit Description:**
   (One sentence maximum. Attach diagram)
   Helmholtz phase discriminator circuit used in a speed loop.

	Probable Cause													
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:
Memory Loss														
Null Shift														
Bias Change						x								
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery						x								
Hysterisis														
Saturation														
Linearity						x								
Deterioration														
Gain Change						x								
Frequency Response														
Instability														
Mechanical														

Other:

Evidence of Probable Cause:
The problem was the use of a sticky (adhesive) surface in the flow channels that picked up dirt.

Date: 9/28/65 Signed: C.W.W.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒
Digital ☐
Counter ☐

Environmental Information:

1. Test Duration Prior to Failure (operational hours):
100 hours

2. Test Conditions at Failure:

a. Cyclic Parameter
Pressure Temperature x
Peak-to-peak Amplitude: Proprietory
Frequency: 2 to 4 KC

b. Steady-state Parameter:

P_S P_{C_L} P_{C_R} P_V P_{R_L} P_{R_R} T_F T_{Amb}

(psig) 70°F

3. Prior History:

4. Corrective Action:

5. Circuit Description:
(One sentence maximum. Attach diagram)
Two element superhet circuit

	Probable Cause													
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:
Memory Loss														
Null Shift														
Bias Change	x			x										
Noise Level	x			x										
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery	x			x										
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change														
Frequency Response														
Instability														
Mechanical														
Other:														

Evidence of Probable Cause:

Circuit plates warped after thermal cycling

Date: 7/65 Signed: L. K.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒
Digital ☐
Counter ☐

Environmental Information:

1. **Test Duration Prior to Failure (operational hours):**
   25 hours
2. **Test Conditions at Failure:**
   - a. **Cyclic Parameter**
     Pressure **Temperature** x
     Peak-to-peak Amplitude: Proprietory
     Frequency: 80 to 160 cps
   - b. **Steady-state Parameter:**

	P_S	P_{C_L}	P_{C_R}	P_V	P_{R_L}	P_{R_R}	T_F	T_{Amb}
(psig)								70°F

3. **Prior History:**
   Laboratory test program
4. **Corrective Action:**
   Rebuilt and resealed circuit
5. **Circuit Description:**
   (One sentence maximum. Attach diagram)
   Six element phase discriminator circuit

Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:Interconnections
Memory Loss														
Null Shift	x													x
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change														
Frequency Response														
Instability														
Mechanical														

(Probable Cause)

Other:

Evidence of Probable Cause:

Circuit null shift

Date: 7/65 **Signed:** L, K.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒

Digital ☐

Counter ☐

Hybrid ☐

Environmental Information:

1. Test Duration Prior to Failure (operational hours):

   16 hours

2. Test Conditions at Failure:

   a. Cyclic Parameter

   Pressure Temperature x

   Peak-to-peak Amplitude: Proprietory

   Frequency: 2 - 4 KC

   b. Steady-state Parameter:

   P_S P_{C_L} P_{C_R} P_V P_{R_L} P_{R_R} T_F T_{Amb}

   (psig)

3. Prior History:

   Two cycles

4. Corrective Action:

   Operate at lower temperature

5. Circuit Description:

   (One sentence maximum. Attach diagram)

   Fluid Oscillation (classified)

	Probable Cause													
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other: Oxidation
Memory Loss														
Null Shift														
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change														
Frequency Response														
Instability														
Mechanical														
Other: Stopped Oscillating			x	x		x								x

Evidence of Probable Cause:

Date: 7/65 Signed: L. K.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒
Digital ☐
Counter ☐

Environmental Information:

1. Test Duration Prior to Failure (operational hours):
16 hours

2. Test Conditions at Failure:

a. Cyclic Parameter
Pressure Temperature x
Peak-to-peak Amplitude: Proprietory
Frequency: 2 to 4 KC

b. Steady-state Parameter:
P_S P_{C_L} P_{C_R} P_V P_{R_L} P_{R_R} T_F T_{Amb}
(psig)

3. Prior History:
Four cycles

4. Corrective Action:
No gasket used

5. Circuit Description:
(One sentence maximum. Attach diagram)
Fluid oscillator (classified)

	Probable Cause													
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other: Torn Gasket
Memory Loss														
Null Shift														
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change														
Frequency Response														
Instability														
Mechanical														
Other: Frequency Shift			x	x										x

Evidence of Probable Cause:

Date: 7/65 Signed: L. K.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☐
Digital ☒
Counter ☐

Environmental Information:

1. **Test Duration Prior to Failure (operational hours):**
   ≈ 6
2. **Test Conditions at Failure:**
   a. **Cyclic Parameter**
      Pressure x Temperature
      Peak-to-peak Amplitude: 2 psi
      Frequency: 100 cps
   b. **Steady-state Parameter:**

	P_S	P_{C_L}	P_{C_R}	P_V	P_{R_L}	P_{R_R}	T_F	T_{Amb}
(psig)	≈2						70°F	

3. **Prior History:**
   None
4. **Corrective Action:**
   Cleaned by alternately vacuuming and pressurizing the ports and vents.
5. **Circuit Description:**
   (One sentence maximum. Attach diagram)
   Five stage shift register assembly SR6C manufactured by Corning. Supply nozzle 0.01-inch wide x 0.016-inch.

	Probable Cause												
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:
Memory Loss						x								
Null Shift														
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change														
Frequency Response														
Instability														
Mechanical														

Other:

Evidence of Probable Cause:

White dust built up in visible areas, same is probably in invisible, more critical, areas. Same dust found in yellow supply hose.

Date: 10/3/65 Signed: D. L. R.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒

Digital ☐

Environmental Information:

1. Test Duration Prior to Failure (operational hours):

   ~10 during circuit debugging

2. Test Conditions at Failure:

   a. Cyclic Parameter

   Pressure x Temperature

   Peak-to-peak Amplitude: ± 25 psi output ΔP

   Frequency: DC up to 25 cps

   b. Steady-state Parameter:

	P_S	P_{C_L}	P_{C_R}	P_V	P_{R_L}	P_{R_R}	T_F	T_{Amb}
(psig)	45	5	5	0	~20	~20	both 70°F	

3. Prior History:

   Operated in laboratory with laboratory line air filter only; after failure test always run with a filter at hardware.

4. Corrective Action:

   Amplifier disassembled, large rust scale particle discovered in interaction region; particle removed and covered reattached.

5. Circuit Description:

   (One sentence maximum. Attach diagram)

   Power amplifier for RL-10 servo circuit

	Probable Cause													
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:
Memory Loss														
Null Shift						x								
Bias Change														
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity						x								
Deterioration														
Gain Change						x								
Frequency Response														
Instability						x								
Mechanical														

Other:

Evidence of Probable Cause:

Amplifier operation erratic, "hard over" signal often occurred.

Date: 10/6/65

Signed: J. N. S.

FLUID AMPLIFIER FAILURE REPORT

Device: Proportional ☒
Digital ☐
Counter ☐
Hybrid ☐

Environmental Information:

1. Test Duration Prior to Failure (operational hours):
   2000 hours
2. Test Conditions at Failure:
   a. Cyclic Parameter
      Pressure Temperature
      Peak-to-peak Amplitude:
      Frequency:
   b. Steady-state Parameter:

	P_S	P_{C_L}	P_{C_R}	P_V	P_{R_L}	P_{R_R}	T_F	T_{Amb}
(psig)	360	280	280	280	310	310	300°F	

3. Prior History:
   See attached (page 51)
4. Corrective Action:
   See attached (page 51)
5. Circuit Description:
   (One sentence maximum. Attach diagram)
   Individual elements in Life test fixture - Tested with 6% wet steam and dry steam.

	Probable Cause														
Failure	Leaks	Input Pressure	Fluid Temperature	Ambient Temperature	Erosion	Clogging	Cavitation	Resonance	Fatigue	Shock	Impedence Match	Vent Pressure	Mfg. Control	Other:
Memory Loss														
Null Shift														
Bias Change					x									
Noise Level														
Cross Talk														
Flow Recovery														
Power Recovery														
Pressure Recovery														
Hysterisis														
Saturation														
Linearity														
Deterioration														
Gain Change					x									
Frequency Response														
Instability														
Mechanical														

Other:

Evidence of Probable Cause:

Visual inspection

Date: 10/8/65 Signed: C. G. R.

Thirteen elements of various materials and geometry were tested under both wet and dry steam conditions. Eleven of the thirteen elements failed by criteria derived by considering a specific application in a steam turbine speed governor. The application could tolerate a 25 percent gain change and a bias change equivalent to five percent of the element power supply. In general, the performance improved with life, linearity improved, and gain increased. This improvement was attributed to surface roughening by erosion and mineral deposition of "carry over" from the boiler feed water and steam mains. The corrective action to be taken is artificial roughing of the walls before use, plus fabrication elements out of chrome steel. Carbon steel elements would have failed in spite of surface roughing because of gross geometry changes due to erosion.

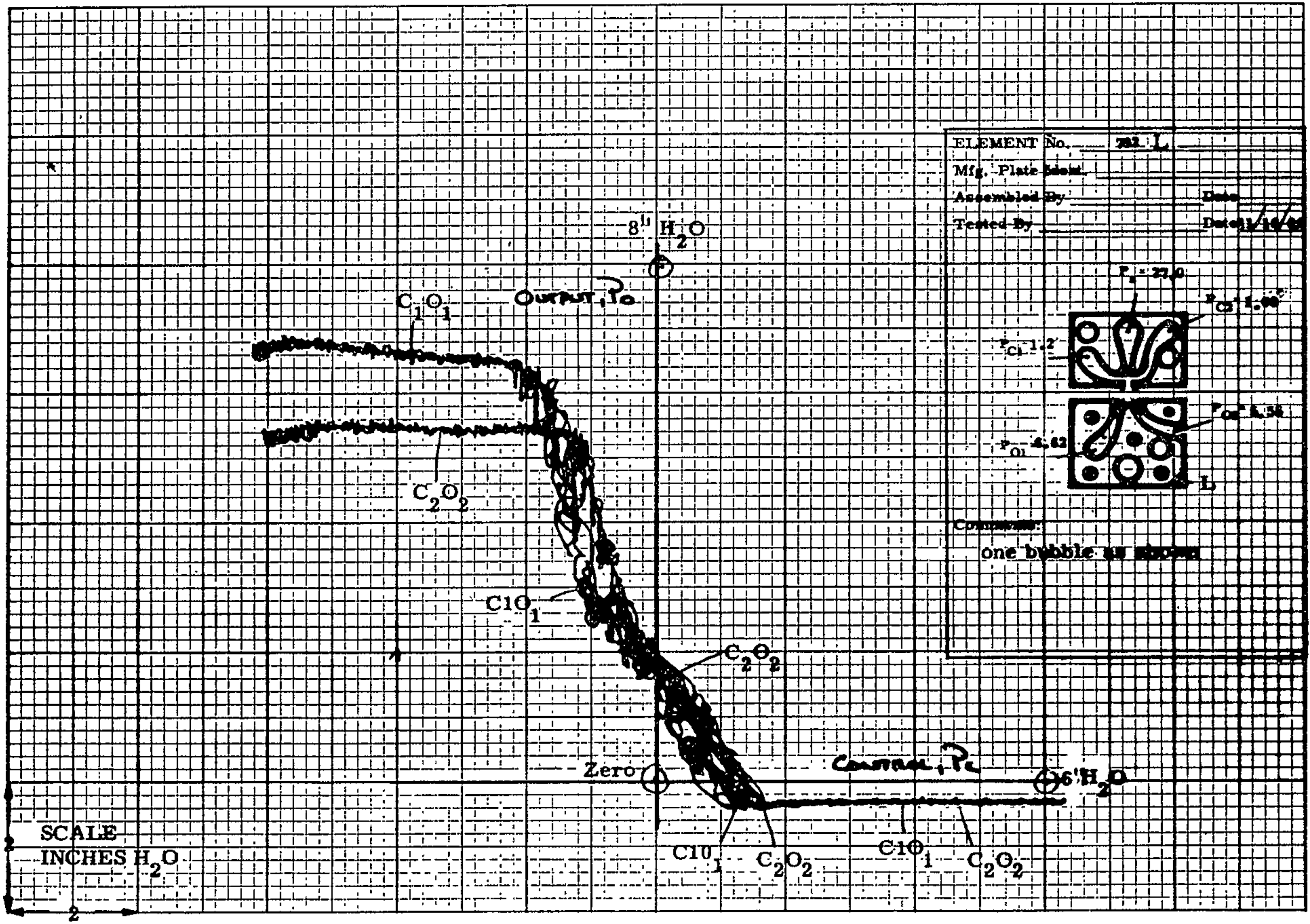
The two elements which passed the test had their surfaces inadvertently roughened by a coating of titanium carbide.

Appendix C

DIGITAL ELEMENT SELECTION

This Appendix summarizes tests conducted prior to the assembly of the fluid amplifier elements into six five-stage shift register circuits. Each element (both gates and flip-flops) was visually inspected and tested in a special test fixture designed to obtain the more critical steady-state parameters (switching and output characteristics). One hundred and twenty elements were fabricated, and the best 90 were then selected for use in six shift register circuits.

All data was obtained using Statham pressure transducers calibrated before each run against water manometers in conjunction with an x-y recorder. Typical data obtained for the 600, 700, and 800 series elements is shown in Figures C-1, C-2, and C-3. For each type element the control pressure is shown on the abscissa and the output pressure is shown on the ordinate. Refer to the sketch at the upper right hand corner for the element outline and the definition of the various pressures of interest. All of the data was taken at a nominal supply pressure of one psig, and each of the elements was loaded with the same size orifice as in the actual circuit. The test data was processed statistically and 25 percent of the elements were rejected.(those exhibiting the greatest deviation from the average). Thus, the final circuits were fabricated from elements having closely matched characteristics. Tables C-1, C-2, and C-3 present the input data (as read from graphs such as Figures C-1, C-2, and C-3) and reduced data for the 600, 700, and 800 series elements. In the reduced data all of the pressures have been normalized to supply and averaged. The deviation of each element from the average, as well as the total standard deviation, is shown. For example, referring to Table C-1, control Port No. 1 of element 601 required 2. 56 in water switching pressure at a supply level of 27 in water (normalized P_{c1}/P_s = 0. 09481). For all of the No. 1 controls the averaged switch pressure was 0. 09092 times the supply with a standard deviation of 8. 81 percent or 0. 222 in water. Element 601 therefore required a normalized switch pressure 0. 0039 above average. Figures C-4 through C-9 show the data plotted on probability coordinates. Since a straight line provided a good fit to the data, it was concluded that the distributions were normal. Table C-4 summarizes all of the normalized results for all of the elements taken as a group and for the best 75 percent of those elements. On the average, a 30 percent reduction in standard deviation per element was achieved by the selection process.



ELEMENT No. 782 L

Mfg. Plate Ident.

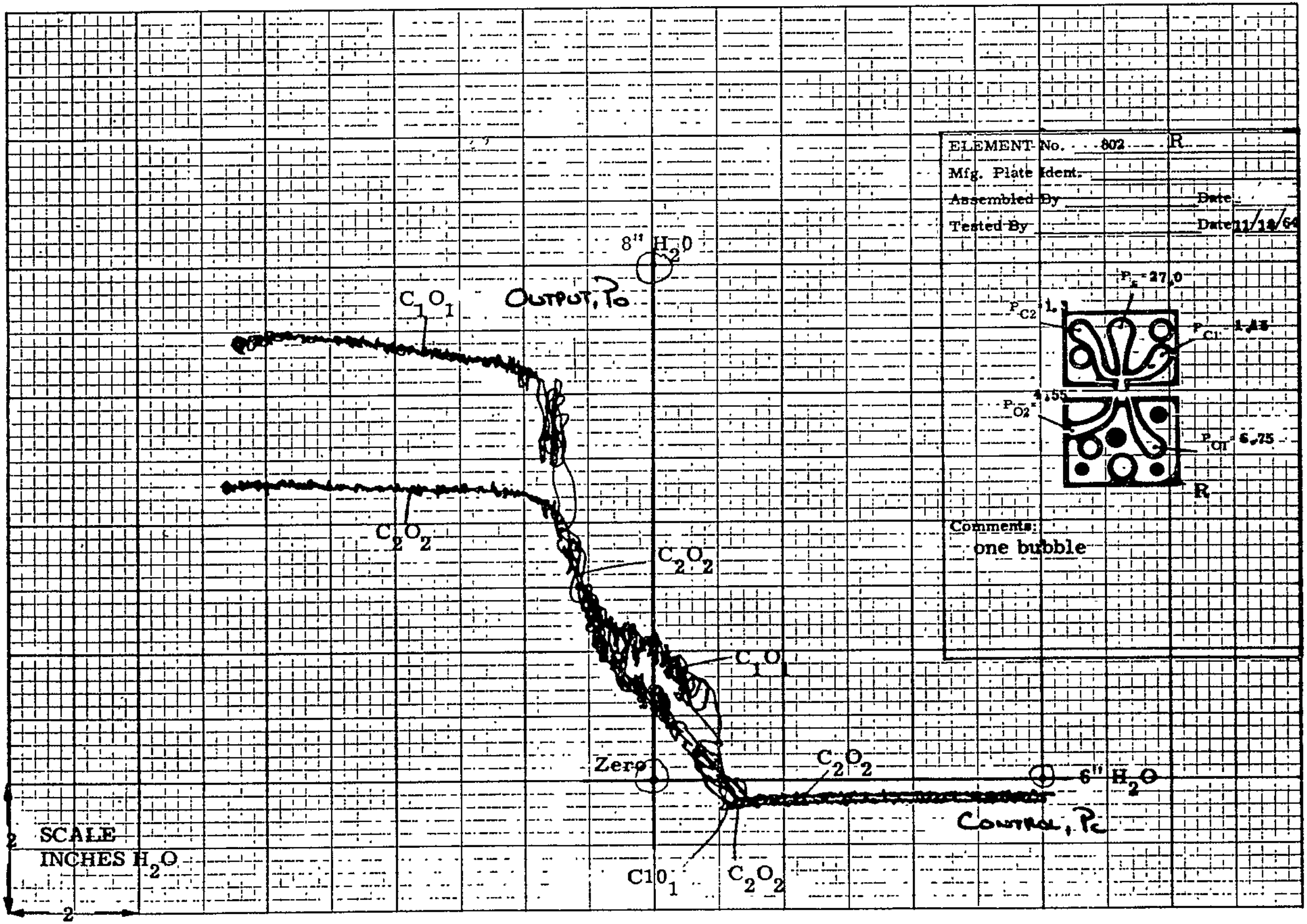
Assembled By Date

Tested By Date 11/16/6

Comments:

one bubble as shown

Figure C-1.



ELEMENT No. 802 R

Mfg. Plate Ident.

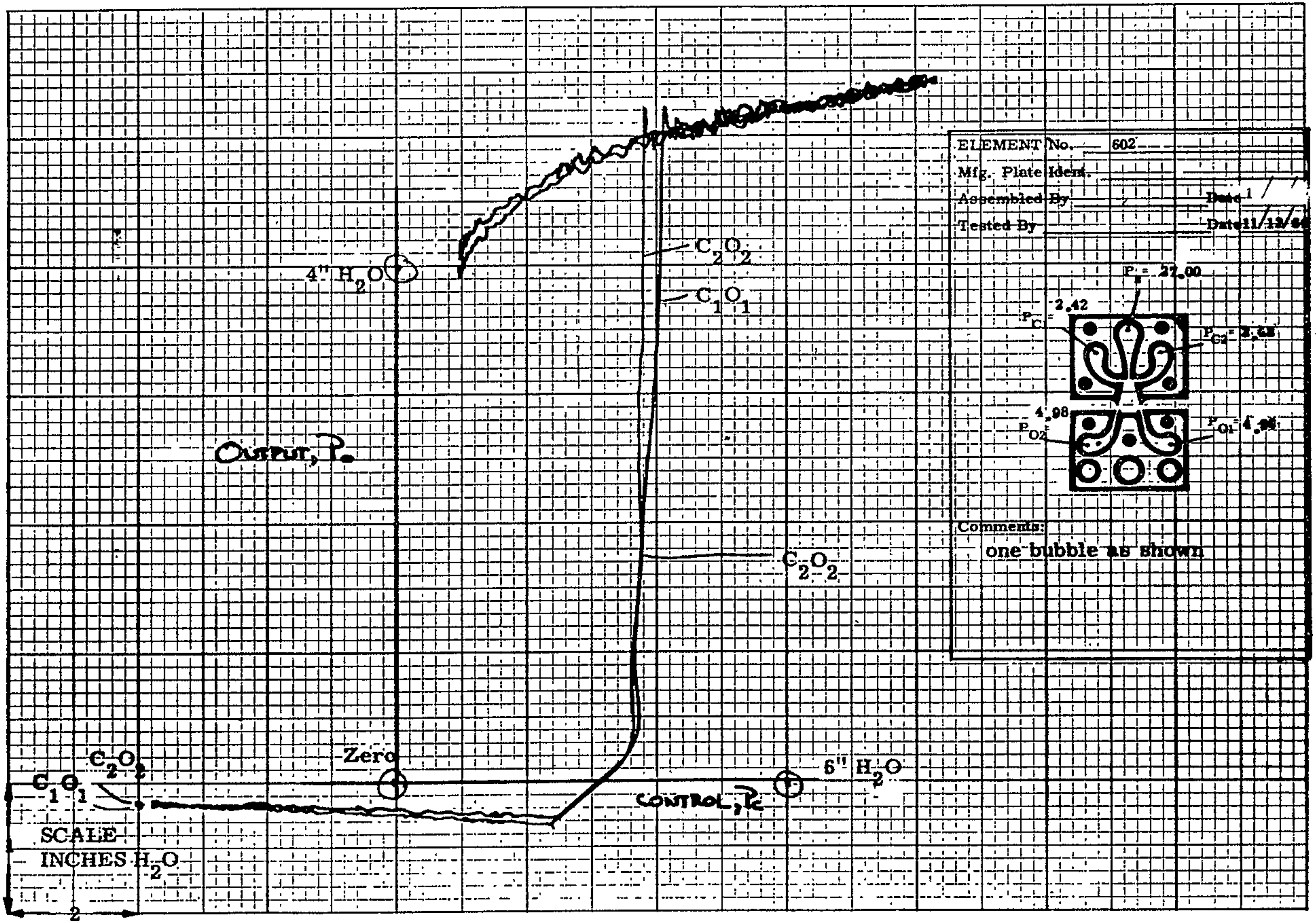
Assembled By Date

Tested By Date 11/12/64

Comments:

one bubble

Figure C-2.



ELEMENT No. 602

Mfg. Plate Ident.

Assembled By Date 1 / /

Tested By Date 11/12/6

Comments:
one bubble as shown

Figure C-3.

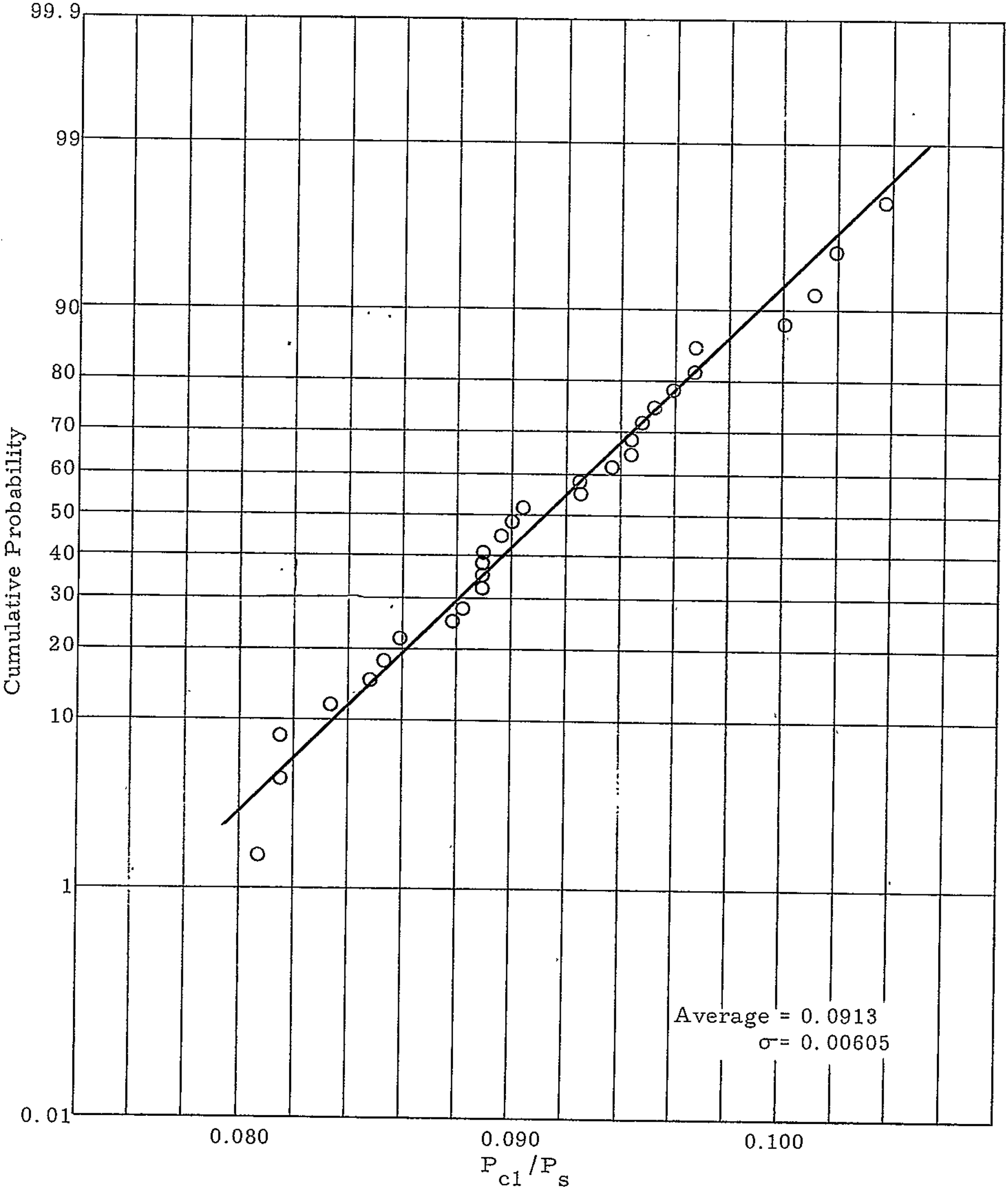


Figure C-4. 600 Series (Flip Flops).

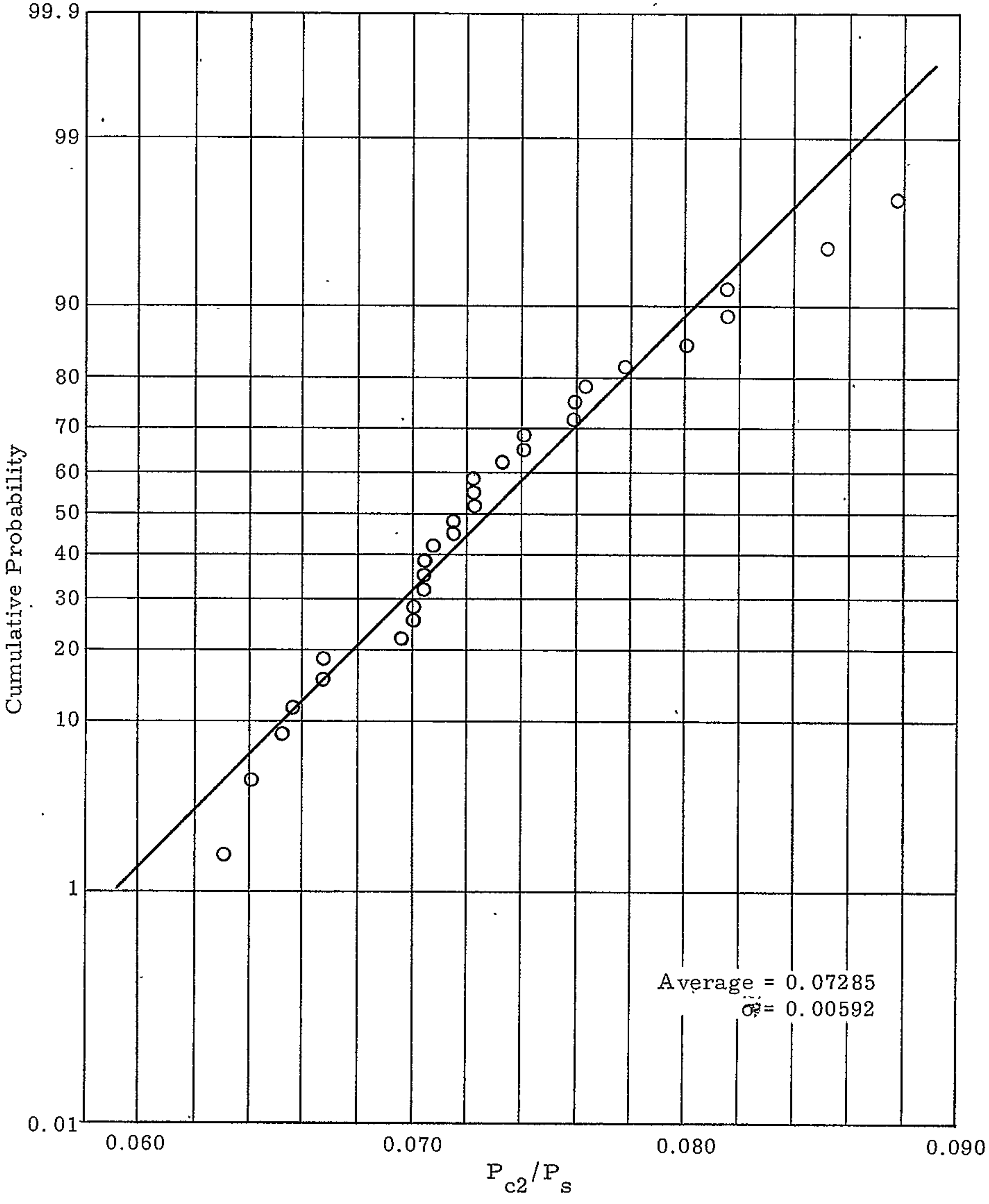


Figure C-5. .600 Series (Flip Flop).

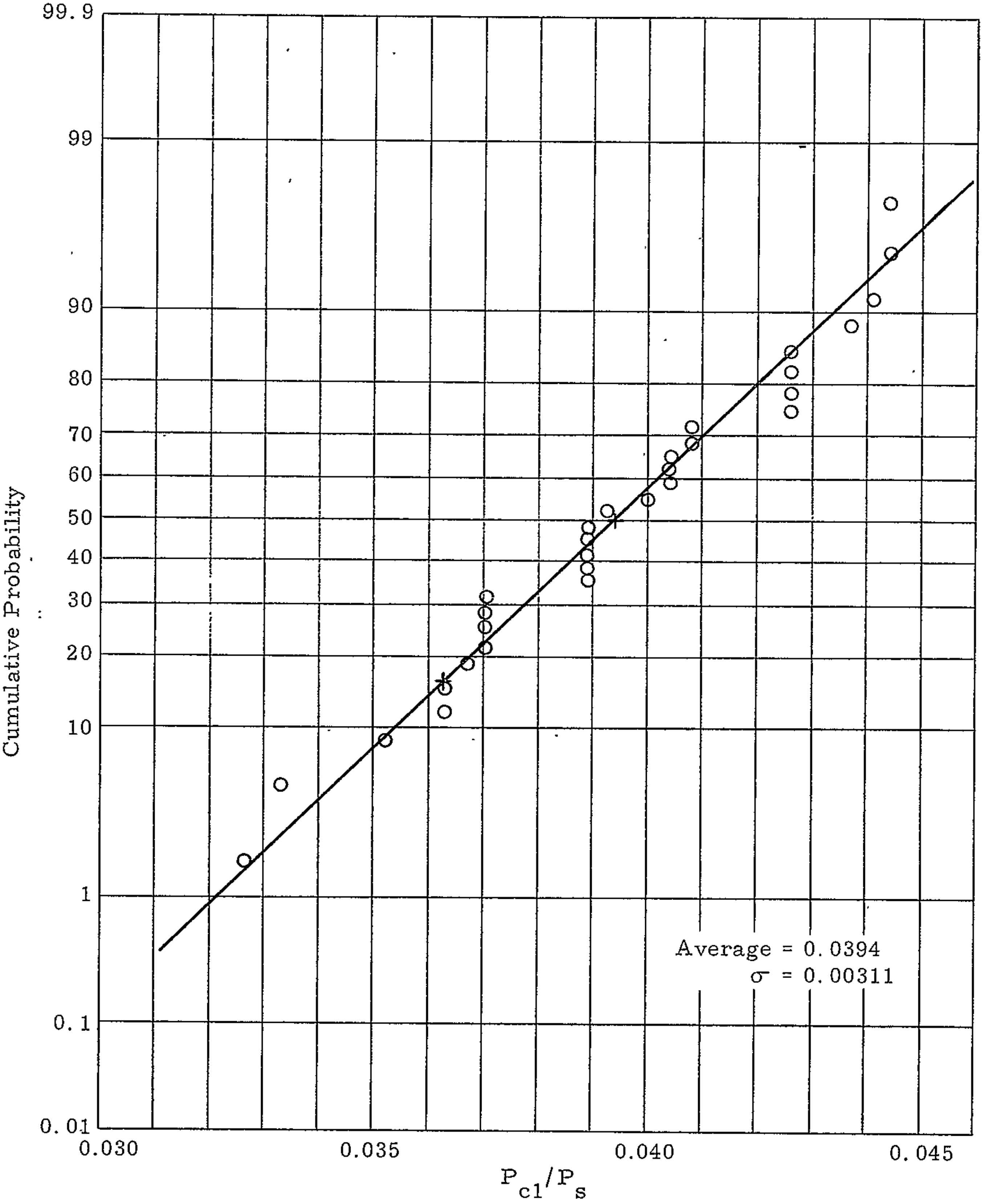


Figure C-6. 700 Series (Left Hand Gates).

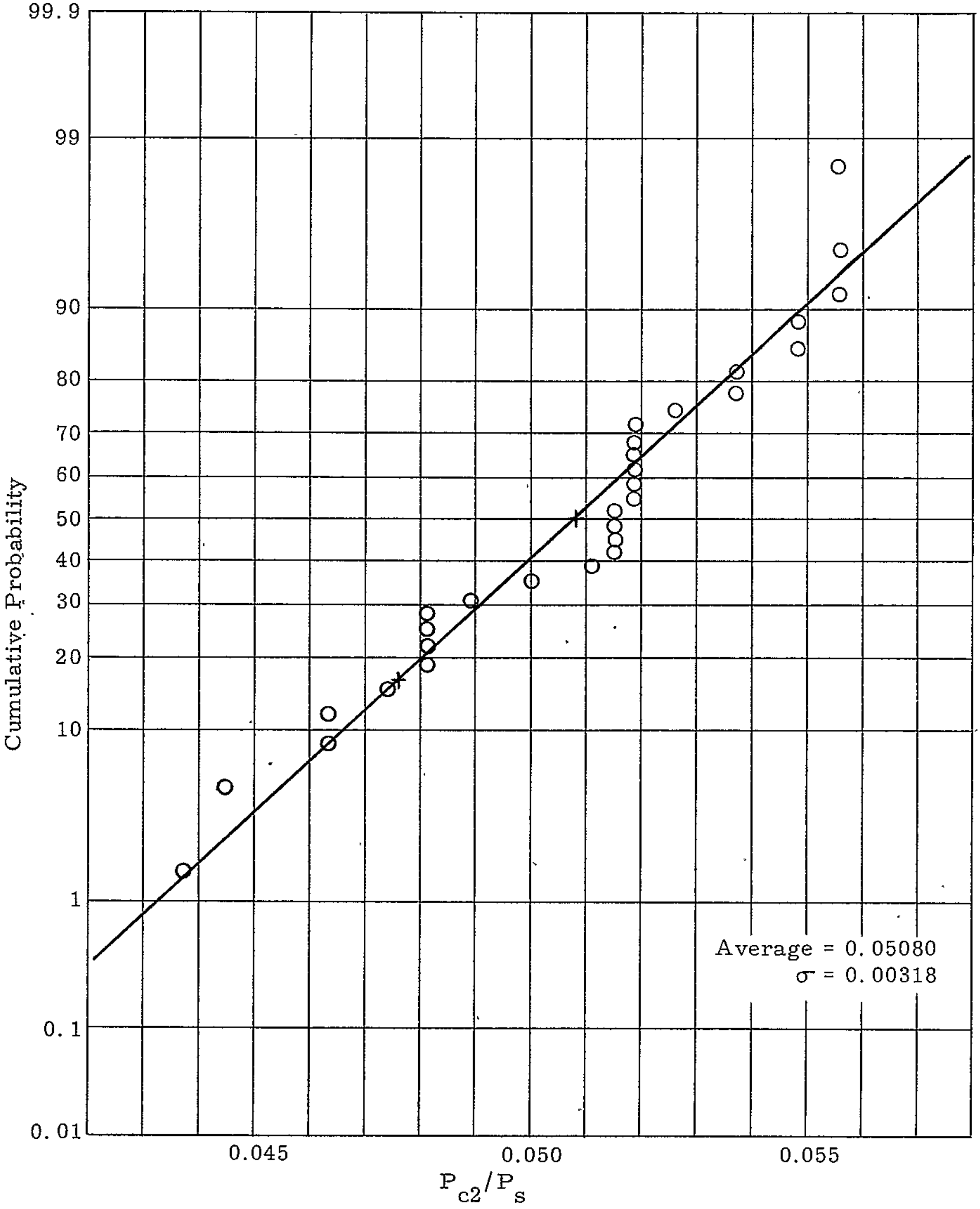


Figure C-7. 700 Series (Left Hand Gates)

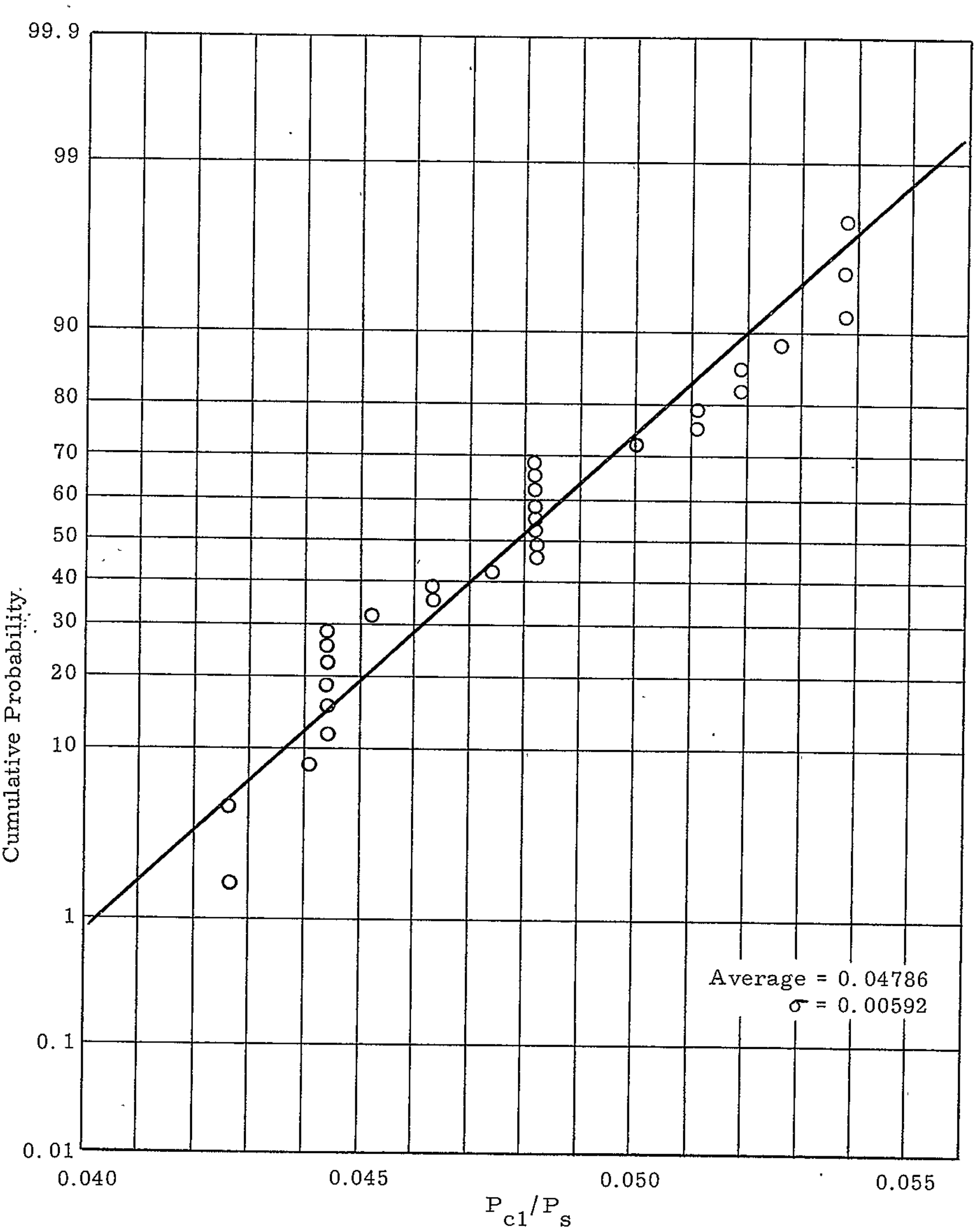


Figure C-8. 800 Series (Right Hand Gates).

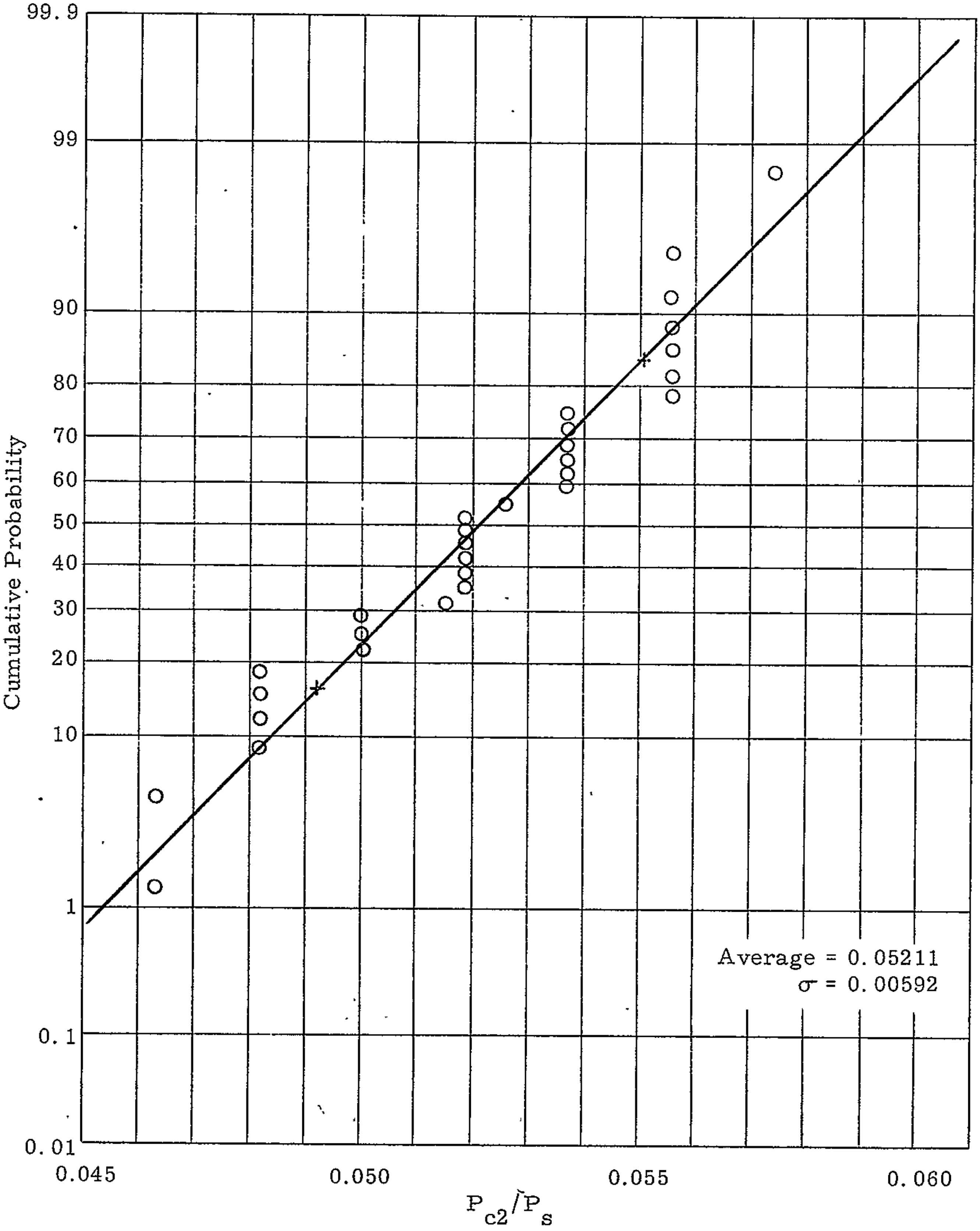


Figure C-9. 800 Series (Right Hand Gates)

Table C-1

INPUT DATA (PRESSURES INH2O GAGE)

ELEM	SUPPLY	CONTROL 1	CONTROL 2	OUTPUT 1	OUTPUT 2
601	27.00000	2.56000	2.10000	4.88000	5.10000
602	27.00000	2.42000	2.48000	4.98000	4.98000
603	27.00000	2.30000	1.90000	5.07000	4.98000
604	27.00000	2.57000	2.05000	4.98000	5.02000
605	27.00000	3.00000	2.20000	4.70000	4.76000
606	27.00000	2.80000	2.16000	5.03000	5.15000
607	27.00000	2.61000	1.80000	4.70000	4.80000
608	27.00000	2.70000	1.95000	5.12000	5.36000
609	27.00000	2.29000	1.70000	5.10000	5.35000
610	27.00000	2.73000	1.90000	5.07000	5.17000
611	27.00000	2.50000	1.91000	4.92000	5.19000
612	27.30000	2.60000	1.38000	4.94000	4.94000
613	27.00000	2.13000	1.60000	5.02000	4.90000
614	27.00000	2.75000	1.88000	4.54000	4.54000
615	27.00000	2.89000	1.70000	4.87000	4.87000
616	27.00000	2.40000	2.00000	4.60000	4.85000
617	27.00000	2.59000	1.89000	4.80000	4.95000
618	27.00000	2.38000	2.06000	4.78000	4.88000
619	27.00000	2.43000	2.20000	4.77000	4.77000
620	27.00000	2.00000	1.80000	5.13000	5.13000
621	27.00000	2.40000	1.76000	5.02000	5.02000
622	27.00000	2.50000	1.95000	5.09000	5.20000
623	27.00000	2.42000	2.37000	4.90000	5.00000
624	27.00000	2.55000	1.73000	5.18000	5.18000
625	27.00000	2.32000	1.93000	4.92000	4.83000
626	27.00000	2.20000	2.30000	4.76000	4.85000
627	27.00000	2.25000	1.90000	5.04000	5.15000
628	27.00000	2.53000	1.93000	4.88000	4.78000
629	27.00000	2.00000	2.10000	4.76000	4.76000
630	27.00000	2.55000	2.00000	4.88000	4.70000
631	27.00000	2.61000	1.95000	4.73000	4.85000
632	27.00000	2.40000	1.77000	4.85000	5.08000
633	27.00000	2.50000	2.40000	4.95000	4.85000
634	27.00000	2.20000	2.20000	4.80000	4.80000
635	27.00000	2.25000	2.40000	4.82000	4.89000
636	27.00000	2.40000	1.89000	5.01000	5.13000
637	27.00000	2.18000	2.05000	5.00000	4.93000
638	27.00000	2.44000	1.98000	4.87000	4.87000
639	27.00000	2.50000	2.52000	4.73000	4.66000
640	27.00000	2.37000	1.80000	5.05000	5.18000

REDUCED DATA

ELEMENT NUMBER	PC1/PS	DELTA PC1/PS	PC2/PS	DELTA PC2/PS	PO1/PS	DELTA PO1/PS	PO2/PS	DELTA PO2/PS
601	0.09481	0.00390	0.07778	0.00410	0.18074	-0.00091	0.18889	0.00524
602	0.08963	-0.00129	0.09185	0.01817	0.18444	0.00279	0.18444	0.00079
603	0.08519	-0.00573	0.07037	-0.00331	0.18778	0.00612	0.18444	0.00079
604	0.09519	0.00427	0.07593	0.00225	0.18444	0.00279	0.18593	0.00227
605	0.11111	0.02019	0.08148	0.00780	0.17407	-0.00758	0.17630	-0.00736
606	0.10370	0.01279	0.08000	0.00632	0.18630	0.00464	0.19074	0.00709
607	0.09667	0.00575	0.06667	-0.00701	0.17407	-0.00758	0.17778	-0.00588
608	0.10000	0.00908	0.07222	-0.00146	0.18963	0.00798	0.19852	0.01487
609	0.08481	-0.00610	0.06296	-0.01072	0.18889	0.00724	0.19815	0.01449
610	0.10111	0.01019	0.07037	-0.00331	0.18778	0.00612	0.19148	0.00783
611	0.09259	0.00167	0.07074	-0.00294	0.18222	0.00057	0.19222	0.00857
612	0.09524	0.00432	0.05055	-0.02313	0.18095	-0.00070	0.18095	-0.00270
613	0.07889	-0.01203	0.05926	-0.01442	0.18593	0.00427	0.18148	-0.00217
614	0.10185	0.01093	0.06963	-0.00405	0.16815	-0.01351	0.16815	-0.01551
615	0.10704	0.01612	0.06296	-0.01072	0.18037	-0.00128	0.18037	-0.00328
616	0.08889	-0.00203	0.07407	0.00039	0.17037	-0.01128	0.17963	-0.00402
617	0.09593	0.00501	0.07000	-0.00368	0.17778	-0.00388	0.18333	-0.00032
618	0.08815	-0.00277	0.07630	0.00262	0.17704	-0.00462	0.18074	-0.00291
619	0.09000	-0.00092	0.08148	0.00780	0.17667	-0.00499	0.17667	-0.00699
620	0.07407	-0.01684	0.06667	-0.00701	0.19000	0.00835	0.19000	0.00635
621	0.08889	-0.00203	0.06519	-0.00850	0.18593	0.00427	0.18593	0.00227
622	0.09259	0.00167	0.07222	-0.00146	0.18852	0.00687	0.19259	0.00894
623	0.08963	-0.00129	0.08778	0.01410	0.18148	-0.00017	0.18519	0.00153
624	0.09444	0.00353	0.06407	-0.00961	0.19185	0.01020	0.19185	0.00820
625	0.08593	-0.00499	0.07148	-0.00220	0.18222	0.00057	0.17889	-0.00476
626	0.08148	-0.00944	0.08519	0.01150	0.17630	-0.00536	0.17963	-0.00402
627	0.08333	-0.00758	0.07037	-0.00331	0.18667	0.00501	0.19074	0.00709
628	0.09370	0.00279	0.07148	-0.00220	0.18074	-0.00091	0.17704	-0.00662
629	0.07407	-0.01684	0.07778	0.00410	0.17630	-0.00536	0.17630	-0.00736
630	0.09444	0.00353	0.07407	0.00039	0.18074	-0.00091	0.17407	-0.00958
631	0.09667	0.00575	0.07222	-0.00146	0.17519	-0.00647	0.17963	-0.00402
632	0.08889	-0.00203	0.06556	-0.00812	0.17963	-0.00202	0.18815	0.00449
633	0.09259	0.00167	0.08889	0.01521	0.18333	0.00168	0.17963	-0.00402
634	0.08148	-0.00944	0.08148	0.00780	0.17778	-0.00388	0.17778	-0.00588
635	0.08333	-0.00758	0.08889	0.01521	0.17852	-0.00313	0.18111	-0.00254
636	0.08889	-0.00203	0.07000	-0.00368	0.18556	0.00390	0.19000	0.00635
637	0.08074	-0.01018	0.07593	0.00225	0.18519	0.00353	0.18259	-0.00106
638	0.09037	-0.00055	0.07333	-0.00035	0.18037	-0.00128	0.18037	-0.00328
639	0.09259	0.00167	0.09333	0.01965	0.17519	-0.00647	0.17259	-0.01106
640	0.08778	-0.00314	0.06667	-0.00701	0.18704	0.00538	0.19185	0.00820
AVERAGE	0.09092		0.07368		0.18165		0.18365	
SIGMA(PCT)	8.610		12.208		3.094		3.787	
SIGMA(H2O)	0.222		0.249		0.154		0.191	

Table C-2

```
INPUT DATA (PRESSURES INH20 GAGE)

ELEM SUPPLY      CONTROL 1 CONTROL 2 OUTPUT 1  OUTPUT 2
 701  27.00000    1.30000   1.60000   6.67000   5.55000
 702  27.00000    1.20000   1.68000   6.62000   5.55000
 703  27.00000    1.08000   1.25000   6.25000   5.38000
 704  27.00000    1.15000   1.28000   5.90000   5.05000
 705  27.00000    1.06000   1.25000   5.80000   5.15000
 706  27.00000    1.20000   1.50000   5.80000   5.10000
 707  27.00000    1.00000   1.40000   6.05000   5.29000
 708  27.00000    1.09000   1.20000   6.38000   5.19000
 709  27.00000    0.85000   1.18000   6.05000   5.05000
 710  27.00000    0.80000   1.30000   5.65000   5.00000
 711  27.00000    0.89000   1.10000   6.15000   5.18000
 712  27.00000    1.15000   1.30000   5.90000   5.10000
 713  27.00000    1.09000   1.30000   6.30000   5.40000
 714  27.00000    0.95000   1.48000   6.50000   5.25000
 715  27.00000    1.10000   1.39000   5.50000   4.95000
 716  27.00000    1.00000   1.30000   6.15000   5.15000
 717  27.00000    1.15000   1.40000   6.00000   4.90000
 718  27.00000    1.05000   1.35000   6.75000   5.35000
 719  27.00000    0.99000   1.38000   6.35000   5.15000
 720  27.00000    0.98000   1.30000   5.78000   4.80000
 721  27.00000    0.88000   1.32000   6.35000   5.20000
 722  27.00000    1.19000   1.39000   6.15000   5.15000
 723  27.00000    1.20000   1.39000   7.30000   6.05000
 724  27.00000    0.80000   1.00000   5.90000   5.10000
 725  27.00000    1.05000   1.18000   6.15000   5.15000
 726  27.00000    1.18000   1.50000   5.80000   5.15000
 727  27.00000    1.05000   1.40000   5.95000   5.10000
 728  27.00000    1.05000   1.40000   6.15000   5.35000
 729  27.00000    0.89000   1.10000   6.19000   4.98000
 730  27.00000    1.09000   1.45000   6.50000   5.25000
 731  27.00000    1.00000   1.39000   6.15000   5.10000
 732  27.00000    1.00000   1.40000   5.75000   5.20000
 733  27.00000    0.87000   1.20000   5.50000   5.95000
 734  27.00000    1.15000   1.45000   6.25000   5.35000
 735  27.00000    1.10000   1.50000   6.02000   5.02000
 736  27.00000    1.05000   1.40000   6.35000   5.05000
 737  27.00000    1.15000   1.60000   6.10000   5.20000
 738  27.00000    0.98000   1.42000   6.30000   4.90000
 739  27.00000    0.90000   1.48000   6.15000   5.18000
```

```
REDUCED DATA

 ELEMENT               DELTA                 DELTA                 DELTA                DELTA
 NUMBER    PC1/PS     PC1/PS     PC2/PS     PC2/PS     PO1/PS     PO1/PS     PO2/PS     PO2/PS
    701    0.04815    0.00953    0.05926    0.00901    0.24704    0.01953    0.20556    0.01280
    702    0.04444    0.00583    0.06222    0.01198    0.24519    0.01768    0.20556    0.01280
    703    0.04000    0.00139    0.04630   -0.00395    0.23148    0.00398    0.19926    0.00651
    704    0.04259    0.00398    0.04741   -0.00284    0.21852   -0.00898    0.18704   -0.00572
    705    0.03926    0.00065    0.04630   -0.00395    0.21481   -0.01269    0.19074   -0.00201
    706    0.04444    0.00583    0.05556    0.00531    0.21481   -0.01269    0.18889   -0.00387
    707    0.03704   -0.00158    0.05185    0.00160    0.22407   -0.00343    0.19593    0.00317
    708    0.04037    0.00176    0.04444   -0.00580    0.23630    0.00879    0.19222   -0.00053
    709    0.03148   -0.00713    0.04370   -0.00654    0.22407   -0.00343    0.18704   -0.00572
    710    0.02963   -0.00898    0.04815   -0.00210    0.20926   -0.01824    0.18519   -0.00757
    711    0.03296   -0.00565    0.04074   -0.00951    0.22778    0.00028    0.19185   -0.00090
    712    0.04259    0.00398    0.04815   -0.00210    0.21852   -0.00898    0.18889   -0.00387
    713    0.04037    0.00176    0.04815   -0.00210    0.23333    0.00583    0.20000    0.00725
    714    0.03519   -0.00343    0.05481    0.00457    0.24074    0.01324    0.19444    0.00169
    715    0.04074    0.00213    0.05148    0.00123    0.20370   -0.02380    0.18333   -0.00942
    716    0.03704   -0.00158    0.04815   -0.00210    0.22778    0.00028    0.19074   -0.00201
    717    0.04259    0.00398    0.05185    0.00160    0.22222   -0.00528    0.18148   -0.01127
    718    0.03889    0.00028    0.05000   -0.00025    0.25000    0.02250    0.19815    0.00539
    719    0.03667   -0.00195    0.05111    0.00086    0.23519    0.00768    0.19074   -0.00201
    720    0.03630   -0.00232    0.04815   -0.00210    0.21407   -0.01343    0.17778   -0.01498
    721    0.03259   -0.00602    0.04889   -0.00136    0.23519    0.00768    0.19259   -0.00016
    722    0.04407    0.00546    0.05148    0.00123    0.22778    0.00028    0.19074   -0.00201
    723    0.04444    0.00583    0.05148    0.00123    0.27037    0.04287    0.22407    0.03132
    724    0.02963   -0.00898    0.03704   -0.01321    0.21852   -0.00898    0.18889   -0.00387
    725    0.03889    0.00028    0.04370   -0.00654    0.22778    0.00028    0.19074   -0.00201
    726    0.04370    0.00509    0.05556    0.00531    0.21481   -0.01269    0.19074   -0.00201
    727    0.03889    0.00028    0.05185    0.00160    0.22037   -0.00713    0.18889   -0.00387
    728    0.03889    0.00028    0.05185    0.00160    0.22778    0.00028    0.19815    0.00539
    729    0.03296   -0.00565    0.04074   -0.00951    0.22926    0.00176    0.18444   -0.00831
    730    0.04037    0.00176    0.05370    0.00346    0.24074    0.01324    0.19444    0.00169
    731    0.03704   -0.00158    0.05148    0.00123    0.22778    0.00028    0.18889   -0.00387
    732    0.03704   -0.00158    0.05185    0.00160    0.21296   -0.01454    0.19259   -0.00016
    733    0.03222   -0.00639    0.04444   -0.00580    0.20370   -0.02380    0.22037    0.02762
    734    0.04259    0.00398    0.05370    0.00346    0.23148    0.00398    0.19815    0.00539
    735    0.04074    0.00213    0.05556    0.00531    0.22296   -0.00454    0.18593   -0.00683
    736    0.03889    0.00028    0.05185    0.00160    0.23519    0.00768    0.18704   -0.00572
    737    0.04259    0.00398    0.05926    0.00901    0.22593   -0.00158    0.19259   -0.00016
    738    0.03630   -0.00232    0.05259    0.00235    0.23333    0.00583    0.18148   -0.01127
    739    0.03333   -0.00528    0.05481    0.00457    0.22778    0.00028    0.19185   -0.00090

AVERAGE    0.03861               0.05025               0.22750               0.19275

SIGMA(PCT) 11.478                10.352                 5.654                 4.705

SIGMA(H2O)  0.123                 0.144                 0.356                 0.251
```

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Table C-3

INPUT DATA (PRESSURES INH20 GAGE)

ELEM	SUPPLY	CONTROL 1	CONTROL 2	OUTPUT 1	OUTPUT 2
801	27.00000	1.20000	1.55000	6.35000	4.60000
802	27.00000	1.15000	1.30000	6.75000	4.55000
803	27.00000	1.20000	1.40000	6.55000	4.39000
804	27.00000	1.20000	1.25000	6.78000	4.42000
805	27.00000	1.28000	1.45000	6.70000	4.40000
806	27.00000	1.02000	1.20000	6.85000	5.00000
807	27.00000	1.22000	1.50000	6.70000	4.18000
808	27.00000	1.30000	1.40000	6.30000	4.20000
809	27.00000	1.04000	1.62000	6.05000	4.35000
810	27.00000	1.20000	1.42000	6.18000	4.30000
811	27.00000	1.00000	1.30000	6.85000	4.60000
812	27.00000	1.35000	1.45000	6.35000	4.45000
813	27.00000	1.38000	1.50000	5.90000	4.10000
814	27.00000	1.30000	1.22000	6.15000	3.90000
815	27.00000	1.30000	1.40000	6.20000	4.00000
816	27.00000	1.19000	1.30000	6.42000	4.10000
817	27.00000	1.25000	1.55000	6.60000	4.45000
818	27.00000	1.30000	1.40000	6.65000	4.40000
819	27.00000	1.40000	1.50000	6.75000	4.58000
820	27.00000	1.45000	1.50000	6.25000	4.25000
821	27.00000	1.20000	1.25000	6.45000	4.65000
822	27.00000	1.15000	1.35000	6.95000	4.55000
823	27.00000	1.30000	1.35000	6.70000	4.10000
824	27.00000	1.45000	1.40000	6.45000	4.25000
825	27.00000	1.20000	1.50000	6.60000	4.05000
826	27.00000	1.40000	1.45000	6.20000	4.35000
827	27.00000	1.20000	1.30000	5.95000	3.75000
828	27.00000	1.25000	1.50000	6.45000	4.00000
829	27.00000	1.30000	1.35000	6.60000	4.05000
830	27.00000	1.45000	1.60000	6.80000	4.50000
831	27.00000	1.50000	1.60000	6.65000	4.40000
832	27.00000	1.30000	1.25000	6.70000	4.60000
833	27.00000	1.38000	1.40000	6.09000	4.50000
834	27.00000	1.20000	1.45000	6.60000	4.90000
835	27.00000	1.42000	1.50000	6.55000	4.45000
836	27.00000	1.30000	1.30000	6.60000	4.30000
837	27.00000	1.30000	1.39000	6.30000	4.15000
838	27.00000	1.45000	1.45000	6.25000	4.59000
839	27.00000	1.55000	1.45000	6.09000	4.00000
840	27.00000	1.45000	1.45000	6.80000	4.40000

REDUCED DAT

ELEMENT NUMBER	PC1/PS	DELTA PC1/PS	PC2/PS	DELTA PC2/PS	PO1/PS	DELTA PO1/PS	PO2/PS	DELTA PO2/PS
801	0.04444	-0.00322	0.05741	0.00509	0.23519	-0.00473	0.17037	0.00948
802	0.04259	-0.00507	0.04815	-0.00417	0.25000	0.01008	0.16852	0.00763
803	0.04444	-0.00322	0.05185	-0.00046	0.24259	0.00268	0.16259	0.00170
804	0.04444	-0.00322	0.04630	-0.00602	0.25111	0.01119	0.16370	0.00281
805	0.04741	-0.00026	0.05370	0.00139	0.24815	0.00823	0.16296	0.00207
806	0.03778	-0.00989	0.04444	-0.00787	0.25370	0.01379	0.18519	0.02430
807	0.04519	-0.00248	0.05556	0.00324	0.24815	0.00823	0.15481	-0.00607
808	0.04815	0.00048	0.05185	-0.00046	0.23333	-0.00658	0.15556	-0.00533
809	0.03852	-0.00915	0.06000	0.00769	0.22407	-0.01584	0.16111	0.00022
810	0.04444	-0.00322	0.05259	0.00028	0.22889	-0.01103	0.15926	-0.00163
811	0.03704	-0.01063	0.04815	-0.00417	0.25370	0.01379	0.17037	0.00948
812	0.05000	0.00233	0.05370	0.00139	0.23519	-0.00473	0.16481	0.00393
813	0.05111	0.00344	0.05556	0.00324	0.21852	-0.02140	0.15185	-0.00904
814	0.04815	0.00048	0.04519	-0.00713	0.22778	-0.01214	0.14444	-0.01644
815	0.04815	0.00048	0.05185	-0.00046	0.22963	-0.01029	0.14815	-0.01274
816	0.04407	-0.00359	0.04815	-0.00417	0.23778	-0.00214	0.15185	-0.00904
817	0.04630	-0.00137	0.05741	0.00509	0.24444	0.00453	0.16481	0.00393
818	0.04815	0.00048	0.05185	-0.00046	0.24630	0.00638	0.16296	0.00207
819	0.05185	0.00419	0.05556	0.00324	0.25000	0.01008	0.16963	0.00874
820	0.05370	0.00604	0.05556	0.00324	0.23148	-0.00844	0.15741	-0.00348
821	0.04444	-0.00322	0.04630	-0.00602	0.23889	-0.00103	0.17222	0.01133
822	0.04259	-0.00507	0.05000	-0.00231	0.25741	0.01749	0.16852	0.00763
823	0.04815	0.00048	0.05000	-0.00231	0.24815	0.00823	0.15185	-0.00904
824	0.05370	0.00604	0.05185	-0.00046	0.23889	-0.00103	0.15741	-0.00348
825	0.04444	-0.00322	0.05556	0.00324	0.24444	0.00453	0.15000	-0.01089
826	0.05185	0.00419	0.05370	0.00139	0.22963	-0.01029	0.16111	0.00022
827	0.04444	-0.00322	0.04815	-0.00417	0.22037	-0.01955	0.13889	-0.02200
828	0.04630	-0.00137	0.05556	0.00324	0.23889	-0.00103	0.14815	-0.01274
829	0.04815	0.00048	0.05000	-0.00231	0.24444	0.00453	0.15000	-0.01089
830	0.05370	0.00604	0.05926	0.00694	0.25185	0.01194	0.16667	0.00578
831	0.05556	0.00789	0.05926	0.00694	0.24630	0.00638	0.16296	0.00207
832	0.04815	0.00048	0.04630	-0.00602	0.24815	0.00823	0.17037	0.00948
833	0.05111	0.00344	0.05185	-0.00046	0.22556	-0.01436	0.16667	0.00578
834	0.04444	-0.00322	0.05370	0.00139	0.24444	0.00453	0.18148	0.02059
835	0.05259	0.00493	0.05556	0.00324	0.24259	0.00268	0.16481	0.00393
836	0.04815	0.00048	0.04815	-0.00417	0.24444	0.00453	0.15926	-0.00163
837	0.04815	0.00048	0.05148	-0.00083	0.23333	-0.00658	0.15370	-0.00719
838	0.05370	0.00604	0.05370	0.00139	0.23148	-0.00844	0.17000	0.00911
839	0.05741	0.00974	0.05370	0.00139	0.22556	-0.01436	0.14815	-0.01274
840	0.05370	0.00604	0.05370	0.00139	0.25185	0.01194	0.16296	0.00207
AVERAGE	0.04767		0.05231		0.23992		0.16089	
SIGMA(PCT)	9.850		7.530		4.186		5.977	
SIGMA(H2O)	0.130		0.109		0.276		0.266	

Table C-4

SUMMARY OF NORMALIZED DATA

	ALL		75 PERCENT	
	Average	1σ (Percent of Average)	Average	1σ (Percent of Average
		600 Series (Flip-flops)		
P_{c1}/P_s	0.0909	8.81	0.0913	6.63
P_{c2}/P_s	0.0737	12.21	0.0729	8.13
P_{o1}/P_s	0.1817	3.06	0.1819	3.16
P_{o2}/P_s	0.1837	3.74	0.1848	3.87
		700 Series (Left Hand Gates)		
P_{c1}/P_s	0.0386	11.48	0.0344	7.89
P_{c2}/P_s	0.0503	10.35	0.0508	6.27
P_{o1}/P_s	0.2275	5.65	0.2281	5.52
P_{o2}/P_s	0.1928	4.71	0.1919	4.17
		800 Series (Right Hand Gates)		
P_{c1}/P_s	0.0477	9.85	0.0479	6.98
P_{c2}/P_s	0.0523	7.53	0.0521	5.64
P_{o1}/P_s	0.2399	4.19	0.2403	4.00
P_{o2}/P_s	0.1609	5.98	0.1599	5.46

APPENDIX A

Test Data

APPENDIX B

Failure Reports

APPENDIX C

Digital Element Selection