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DORMANCY AND POWER ON-OFF CYCLING EFFECTS ON ELECTRONIC EQUIPMENT AND PART RELIABILITY

MARTIN MARIETTA AEROSPACE

PREPARED FOR
ROME AIR DEVELOPMENT CENTER

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Martin Marietta has conducted two 12-month programs. The first was to collect, study, and analyze reliability information and data on dormant military electronic equipment and parts and to develop current dormant failure rates, factors, and prediction techniques. The second was to collect, study, and analyze reliability information and data on military electronic systems subjected to power on-off cycling, to correlate failure incidence

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with power on-off cycling, and to quantify power on-off cycling effects with respect to the dormancy and operating states.

This data has been processed and presented in the form of dormant and cyclic failure rates and factors by part types and subtypes for various part classes. Dormancy failure rate and cyclic ratio factor charts have been constructed and partially validated. Environmental effects on the various part classes are discussed, together with factors relating them to one another in other energy states.

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FOREWORD

This final report was prepared by the Orlando Division of Martin Marietta Aerospace, Orlando, Florida, under Contracts No. F30602-72-C-0243 and F30602-72-C-0247, Job Order Nos. 55190252 and 55190253. It covers the period from March 1972 to May 1973. This report was prepared under the direction of Mr. T. R. Gagnier. Major technical contributors to the report were J. A. Bauer, D. F. Cottrell, T. R. Gagnier, Lincoln E. Hall, Edwin W. Kimball, Thomas E. Kirejczyk, Bartlett B. Lewis, William M. Maynard, Theodore Romans, and Charles H. Turner. Additional technical information and support was supplied by other Martin Marietta Aerospace groups, notably, Richard W. Burrows, Denver Division, and Dr. John Venables, Corporate R&D Laboratories/Research Institute for Advanced Studies. The RADC Project Engineer was Mr. Lester J. Gubbins (RBRS).

This report has been reviewed by the Office of Information, RADC, and approved for release to the National Technical Information Service (NTIS).

This report has been reviewed and is approved.

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ABSTRACT

Martin Marietta Aerospace has conducted two 12-month programs. The first was to collect, study, and analyze reliability information and data on dormant military electronic equipment and parts and to develop current dormant failure rates, factors, and prediction techniques. The second was to collect, study, and analyze reliability information and data on military electronic systems subjected to power on-off cycling, to correlate failure incidence with power on-off cycling, and to quantify power on-off cycling effects with respect to the dormancy and operating states.

Over 276 billion part-hours of dormancy information on various part classes have been collected from all known sources. Of these data, approximately 55 billion part-hours are on Military Standard parts, 205 billion on high reliability parts, and 16 billion on "ultimate reliability" devices. Of the 276 billion part-hours, approximately 11 billion are on microelectronic devices.

About 118 billion part-cycles of power on-off information on various part classes have also been accumulated from all known sources. Of these data, approximately 177 million part-cycles are on military standard parts and 118 billion part-cycles on high reliability parts of which 30 billion part-cycles are on microcircuits in system applications. In addition, 24 million part-cycles of vendor microelectronic devices have also been collected and reported.

These data have been processed and presented in the form of dormant and cyclic failure rates and factors by part types and subtypes for various part classes. Dormancy failure rate and cyclic ratio factor charts have been constructed and partially validated. Environmental effects on the various part classes are discussed together with factors relating them to one another in other energy states.

No testing was performed; therefore, no hardware was available for detailed failure mode and failure mechanism analysis. Martin Marietta, however, has several on-going programs under which current and detailed long life failure modes, failure mechanisms, design guidelines, potential problems, test methods, and process control requirements have been prepared. These data have been garnered and culled; only information applicable to dormancy and power on-off cycling failure modes have been included in this report

Reliability modeling techniques, including the states of storage, dormancy, power on-off cycling, and normally energized (operating), have been developed for military electronic equipment and parts. These techniques are based on interrelationships between the storage, dormancy, power on-off cycling, and energized states and have been initially validated.

In addition, the modeling techniques can also be judiciously applied to reliability prediction for any individual state or combination of states. An expansion of the basic modeling technique will permit parametric trade-offs for system reliability to be made. Thus, realistic weapon system operational and maintenance decisions can be made to obtain optimum reliability while achieving required operational capability within system cost and time constraints.

EVALUATION

1. The objectives of this study were (1) to develop failure rates of electronic parts as used in dormant systems and (2) to determine the power on-off cycling effects on electronic parts. This was to be accomplished through the collection and analysis of failure data from military electronic equipment and systems.

2. The first objective, electronic part dormant failure rates, was fairly well accomplished. Sufficient data were available to develop dormant failure rates including quantitative differences among the various quality levels as cited in military part specifications and standards. Of course, engineering judgement played a part in the analysis where data gaps existed. Nevertheless, the final results appear reasonably valid and can be used in dormant system analysis.

3. Limited success was achieved in working toward the second objective, power on-off cycling effects. Only a small amount of data were available and these came from laboratory tests of equipment. The analysis was strongly tempered with engineering judgement and, because of the limited data base, the conclusions regarding power cycling should be treated as tentative. The cycling analysis does provide a framework and a laboratory failure rate baseline for future work. However, a considerably larger data base is required in order to determine cycling effects in actual equipment environments. How this data base might be developed is outlined in the report recommendations; however, considerable resources would be needed.

Lester J. Gubbins

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Rel. & Maint. Engineering Section
Reliability Branch

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1.0 INTRODUCTION

The great majority of available data concerning electronics reliability describes the effects of stresses occurring during the normal operation (power-on) of equipment. Documents such as RADC Reliability Notebook and MIL-HDBK-217A depict in detail operational failure rate data, derating factors, environmental factors, quality factors, etc. Little or nothing is extant on the other states of activation -- storage, dormancy, and power on-off cycling.

A pioneering effort in this direction is contained in RADC-TR-67-307 "Dormant Operating and Storage Effects on Electronic Equipment and Part Reliability" (Reference 1). Data contained in RADC-TR-67-307 are primarily on stored devices, from 8 to 15 years old, and can be considered obsolete with the advances in the state-of-the-art in microelectronic and some semiconductor devices.

The mission requirement operational capabilities of some systems demand long periods of storage, dormancy, and/or cyclic operation. A total systems analysis model is not widely available by which reliability trade-off studies, assessments, and logistic planning can be made to determine the best design approach under cost and operational requirements constraints. Complete data for this total reliability systems model are not available for dormancy or for power on-off cycling. Additional quantification of dormancy effects and power on-off cycling effects is required.

In order to obtain a more comprehensive and current quantification of dormancy failure rates and factors and to gain a better understanding of power on-off cycling effects on electronic equipment reliability, Rome Air Development Center (RADC) awarded two separate contracts to Martin Marietta in February, 1972. These are:

F 30602-72-C-0243 "Dormancy Failure Rates of Electronic Equipment and Parts" and,

F 30602-72-C-0247 "Power On-Off Cycling Effects on Electronic Equipment Reliability."

Certain system interrelationships for storage, dormancy, power on-off cycling, and energized states have been derived and corresponding mathematical models constructed. The derivation and application of these models are discussed in Section 1.1, which also gives an illustrative example of some of their uses and limitations as applied to reliability system analyses.

Section 2.0 gives a brief summary of the important findings, which are presented in tabular form.

Section 3.0 contains the detailed discussion of the dormancy study and Section 4.0 contains the power on-off study.

Section 5.0 presents service life, dormancy, and power on-off models for electronic systems.

Section 6.0 contains conclusions and recommendations from Sections 3.0 and 4.0.

Section 7.0 is the Glossary and defines the terms used herein while Section 8.0 contains a description of pertinent symbols.

Sections 9.0 and 10.0 contain the References and Bibliography, respectively.

1.1 Interrelationship

1.1.1 General

In order to define in quantitative terms the interrelationship of dormancy and power on-off cycling, one must make the assumption that the expected number of failures during the service life of an electronic system is equal to the sum of the expected number of failures during each of its states of activation over its total service life. The principal states of activation are storage (zero activation level), dormancy (ten percent or less of normal activation level), power on-off cycling (from zero activation level to normal activation level and back to zero activation level or vice versa), and energized (normal activation level). Storage and dormancy include such phases as depot storage, handling, transportation, standby, stowage, ready alert, etc. Power on-off cycling may be considered to include all power on-off cycles which occur during testing, checkout, maintenance, repair, alert, operation, etc.

1.1.2 Quantitative Relationships and Formulas

The basic failure relationship can thus be readily modeled:

$$F_{SL} = \sum_{i=1}^{n=4} F_i = F_S + F_D + F_C + F_E \qquad \text{(Equation 1.1.2-1)}$$

Note: Symbols are referred to in Section 8.0.

For a mature electronic system, which has been burned in beyond infant mortality but not reached wearout, the failure rate has been generally assumed to be constant rather than decreasing or increasing. In general terms this hypothesis can be stated:

either $F = \lambda t$ (Equation 1.1.2-2)

or $F_C = \lambda_C C$ (Equation 1.1.2-3)

Substitution of Equations 1.1.2-2 and 1.1.2-3 into 1.1.2-1 yields the following expression:

$$\lambda_{SL}\, t_{SL} = \lambda_S\, t_S + \lambda_D\, t_D + \lambda_C\, C + \lambda_E\, t_E$$

$$\lambda_{SL} = \lambda_S \left(\frac{t_S}{t_{SL}}\right) + \lambda_D \left(\frac{t_D}{t_{SL}}\right) + \lambda_C \left(\frac{C}{t_{SL}}\right) + \lambda_E \left(\frac{t_E}{t_{SL}}\right)$$

(Equation 1.1.2-4)

By substituting $r_S = \frac{t_S}{t_{SL}}$, $r_D = \frac{t_D}{t_{SL}}$, $N_C = \frac{C}{t_{SL}}$, and $r_E = \frac{t_E}{t_{SL}}$, Equation 1.1.2-4 can be simplified to Equation 1.1.2-5,

$$\lambda_{SL} = \lambda_S\, r_S + \lambda_D\, r_D + \lambda_C\, N_C + \lambda_E\, r_E \qquad \text{(Equation 1.1.2-5)}$$

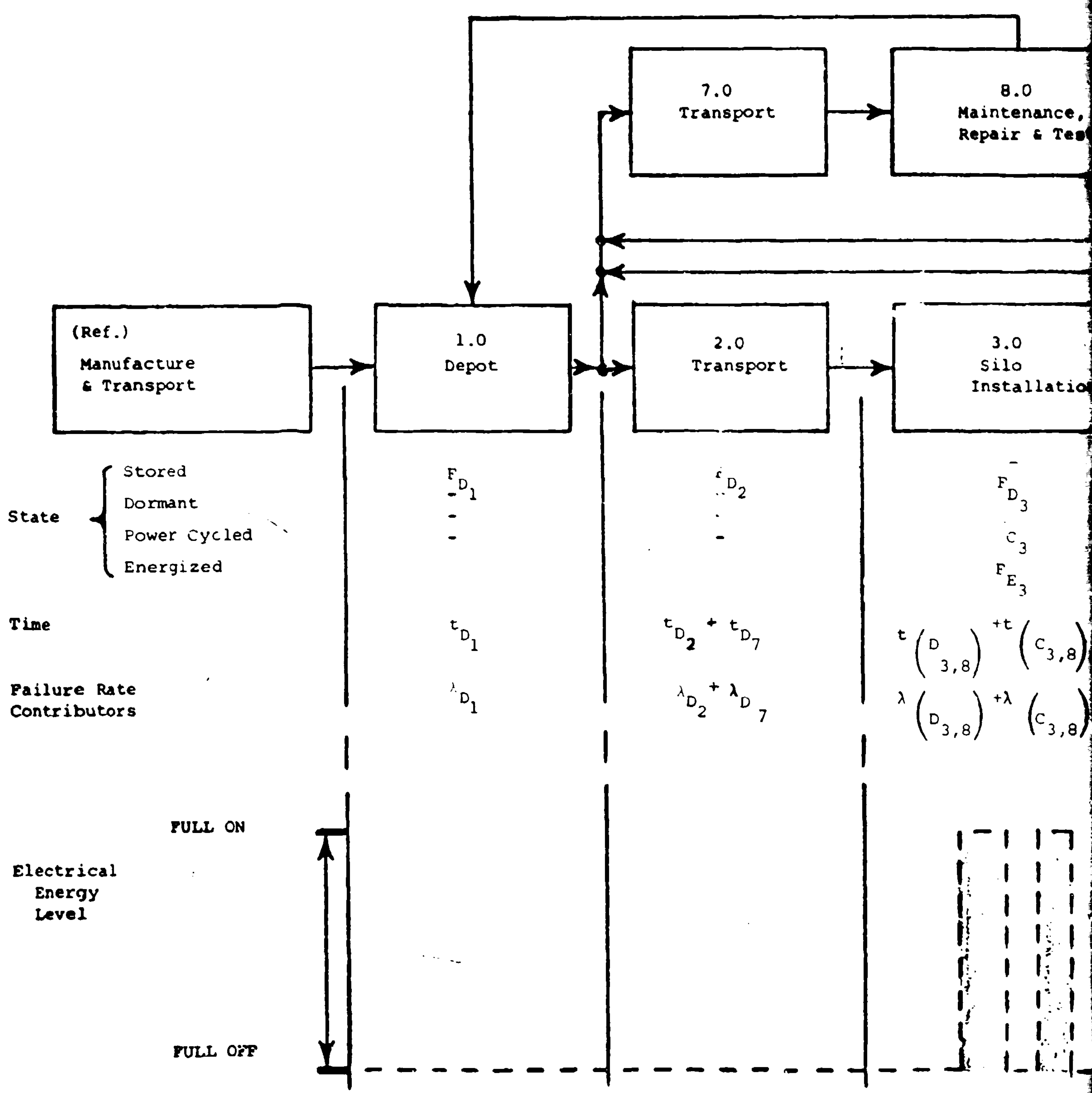
Figure 1.1.2-1 depicts a hypothetical service life cycle that an electronic missile system might be expected to undergo. It illustrates the meanings, development, and association of the various terms, symbols, and expressions used in the foregoing equations. This simplified example assumes no failure contribution prior to depot storage. Practically speaking, however, storage at the manufacturing plant, the final test at the manufacturing plant, or even shipping from the manufacturing plant may be as great a failure contributor as depot storage alone. These would necessarily have to be accounted for in an overall, service life model. Complicating the situation further is the fact that some subsystems within a given system may be dormant while others may be energized. An example of this is power supplies or constant monitor circuitry. Still other subsystems such as environmental control systems may be power on-off cycled. Thus, in reality, the system model of Figure 1.1.2-1 would have to be expanded to the subsystem level to depict accurately subsystem activation states in order to develop truer quantitative terms.

Simple and readily usable mathematical models can be postulated for relationships among storage, dormancy, power on-off cycling, and energized. These are based upon Equations 1.1.2-1 through 1.1.2-5 and the observations made on more than one trillion part-hours and part-cycles of electronic system experience in dormancy and on-off cycling with known reliability grade parts. A review of the experience data has been made, and the postulations corroborated for the relationship of storage to dormancy and the relationship of dormancy to power on-off cycling for similar and identical groups of electronic equipment under a variety of environments.

The relationship of the storage failure rate (λ_S) to the dormant failure rate (λ_D) has been found to vary over a narrow range from unity up to $2\lambda_S = \lambda_D$ for specific components. In considering an average electronic part failure rate for an entire system, no significant statistical difference has been found to exist between storage and dormancy for the same quality of parts over a wide range of nonoperating applications and environments. This means that Equation 1.1.2-5 can be restructured by redefining dormancy and storage as the same state of activation and eliminating one of the terms from the equations.

Another relationship has also been postulated between full power on-full power off cycling and the dormancy failure rate; that is,

$$K_{C/D} = \frac{\lambda_C}{\lambda_D} \approx K_{C/S} = \frac{\lambda_C}{\lambda_S} \qquad \text{(Equation 1.1.2-6)}$$



7.0
Transport
8.0
Maintenance,
Repair & Tes
(Ref.)
Manufacture
& Transport
1.0
Depot
2.0
Transport
3.0
Silo
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FULL ON
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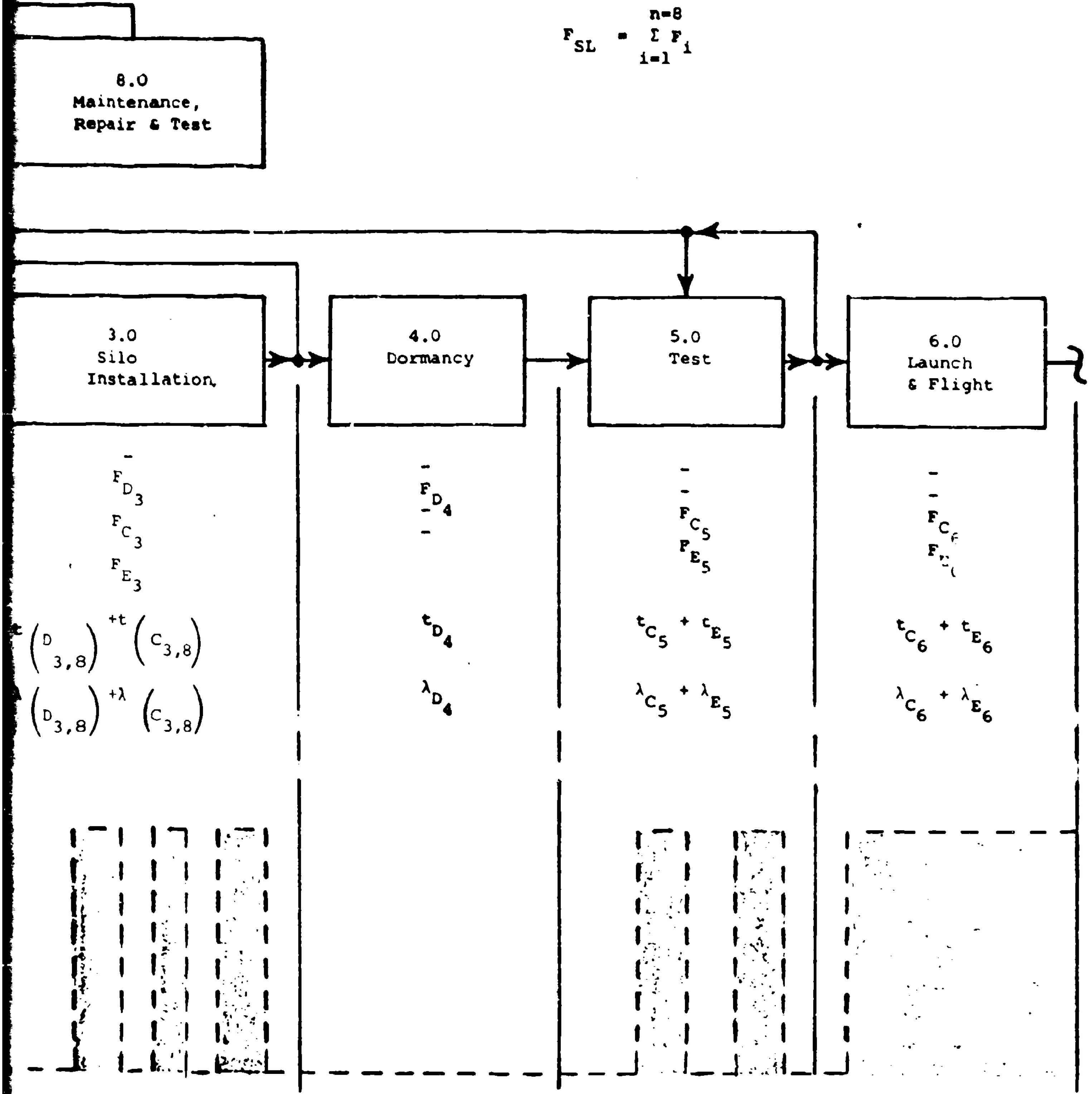


Figure 1.1.2-1 Derivation of Contributors to the Overall Failure Rate of a System During Its Service Life Cycle

It is understood that cyclic failure rates and ratios to dormancy failure rates are dominated by such characteristics as:

1 Part type

2 Part quality (classification)

3 Cyclic rate

4 Combined temperature effects caused by electrical energy versus parts derating, thermal lag, etc.

5 Transient suppression protection

6 Environmental application.

In order to isolate the effects of the above factors, an enormous quantity of data on identical components and parts is required. These data are simply not available. Sufficient data, however, have become available to establish a cumulative cycling effect on generic classes of parts. The ratio $K_{C/D}$ may potentially vary from one to greater than 375 hours of dormancy per cycle.

These observations suggest at least three things:

1 A simplification of Equation 1.1.2-5 can be readily and legitimately accomplished for engineering analysis purposes

2 A review must be made of the methodology used in establishing test versus no test concepts

3 Modeling techniques by which the frequency of periodic testing is established must be updated.

In regards to simplifying Equation 1.1.2-5, $\lambda_S r_S$ can be grouped with $\lambda_D r_D$ since $\lambda_D \approx \lambda_S$; Equation 1.1.2-5 reduces to:

$$\lambda_{SL} = r_S \lambda_D + r_D \lambda_D + \lambda_C N_C + \lambda_E r_E$$

$$\lambda_{SL} = (r_S + r_D) \lambda_D + \lambda_C N_C + \lambda_E r_E \qquad \text{(Equation 1.1.2-7)}$$

and substituting in Equation 1.1.2-6, $\lambda_C = K_{C/D} \lambda_D$

$$\lambda_{SL} = (r_S + r_D) \lambda_D + N_C (K_{C/D} \lambda_D) + \lambda_E r_E$$

$$\lambda_{SL} = (r_S + r_D + N_C K_{C/D}) \lambda_D + \lambda_E r_E \quad , \qquad \text{(Equation 1.1.2-8)}$$

Since $r_S + r_D + r_E = 1$ and when r_E approaches 0, then $r_S + r_D \rightarrow 1$. For systems which must undergo long term storage and dormancy and are energized 1 percent or less of their service life, Equation 1.1.2-8 evolves into Equation 1.1.2-9 which greatly simplifies the quantitative relationship for the storage, dormancy, power on-off cycling, and energized states. This does not imply the term $\lambda_E r_E$ should be ignored for the equipment operating portions of the mission.

$$\lambda_{SL} \approx (1 + K_{C/D} N_C)\lambda_D \qquad \text{(Equation 1.1.2-9)}$$

Use of Equation 1.1.2-9 can be expected to have approximately a five percent error or less when $r_S + r_D \geq 0.99$.

The combined effects of storage, dormancy, and power turn on - turn off can now be readily estimated by the use of Equation 1.1.2-9 for making reliability comparisons or for use in trade-offs as Table 1.1.2-I illustrates.

Use of columns (4) and (5) of Table 1.1.2-I yields equivalent expected degradation values as a function of test frequency. These values can then be directly evalu d or incorporated into parametric trade-off studies which are used to decide testing philosophy or to optimize test intervals once periodic testing has been decided upon.

TABLE 1.1.2-I

Estimates of Service Life Failure Rates and Failures for a **HYPOTHETICAL** High Reliability Electronic System

(1) Expected Number of Power On-Off Cycles		(2) Power On-Off Cycling Ratio (B)	(3) Expected Dormant Failure Rate (C)	(4) Expected Service Life Failure Rate	(5) Expected Number of Service Life Failures
Cycles	Cycles / Service Life (A)	Dormancy Hours / Cycle	Failures / Dormant Hour	Failures / Hour	Failures
(C)	(N_C)	($K_{C/D}$)	(λ_D)	$\lambda_{SL} = (1+K_{C/D}N_C)\lambda_D$	(P_{SL})
0	$0/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(1.000)(20,000 \times 10^{-9})$	1.000
1	$1/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(1.005)(20,000 \times 10^{-9})$	1.005
10	$10/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(1.05)(20,000 \times 10^{-9})$	1.050
100	$10^2/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(1.5)(20,000 \times 10^{-9})$	1.500
1,000	$10^3/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(6)(20,000 \times 10^{-9})$	6.000
10,000	$10^4/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(51)(20,000 \times 10^{-9})$	51.000
100,000	$10^5/5 \times 10^4$	250	$20,000 \times 10^{-9}$	$(501)(20,000 \times 10^{-9})$	501.000

(A) Service life assumed to be 50,000 calendar hours with less than 400 energized hours accrued during the service life so that $r_s + r_D \geq 0.99$.

(B) $K_{C/D}$ assumed on mix of parts, circuit design parameters, derating, cyclic duration, cyclic rate, and transient suppression protection.

(C) λ_D is based on a hypothetical system containing 10,000 electronic parts and having an average dormant λ_D of 2 failures/10^9 part-hours.

Figure 1.1.2-2 graphically illustrates the relationship of the power on-off cycle frequency versus expected number of service life failures for Table 1.1.2-I. Construction and use of figures, such as 1.1.2-2, permit rapid determination of quantitative values for trade-off studies and reliability comparisons.

1.1.3 Validation of Relationships and Formulae

In order to corroborate Equation 1.1.2-9 and preceding equations, a prediction for the Apollo data of Section 4.2.3 has been made and then compared to the actual Apollo failure rate experience on electronic devices.

A. <u>Expected Failure Prediction for Apollo</u>:

Check for $r_S + r_D \geq 0.99$:

$$r_S + r_D + r_E = 1 \qquad \text{where} \quad r_E = \frac{0.4748 \times 10^9}{15.8559 \times 10^9} = 0.03$$

$$r_S + r_D + 0.03 = 1$$

$$r_S + r_D = 0.97$$ which is not ≥ 0.99; therefore an error of approximately 20% low can be expected for the prediction by the approximate method versus actual experience.

B. <u>Prediction by Approximate Method (Equation 1.1.2-9)</u>:

$$\lambda_{SL} = (1 + K_{C/D} N_C) \lambda_D$$

where $K_{C/D} = K_{C/S} = 375$ hours/cycle

$$N_C = \frac{5 \text{ cycles}}{\text{month}} = \frac{5 \text{ cycles}}{730 \text{ hours}}$$

$$\lambda_D = 0.39 \frac{\text{failures}}{10^9 \text{ hours}}$$ for high reliability electronic parts

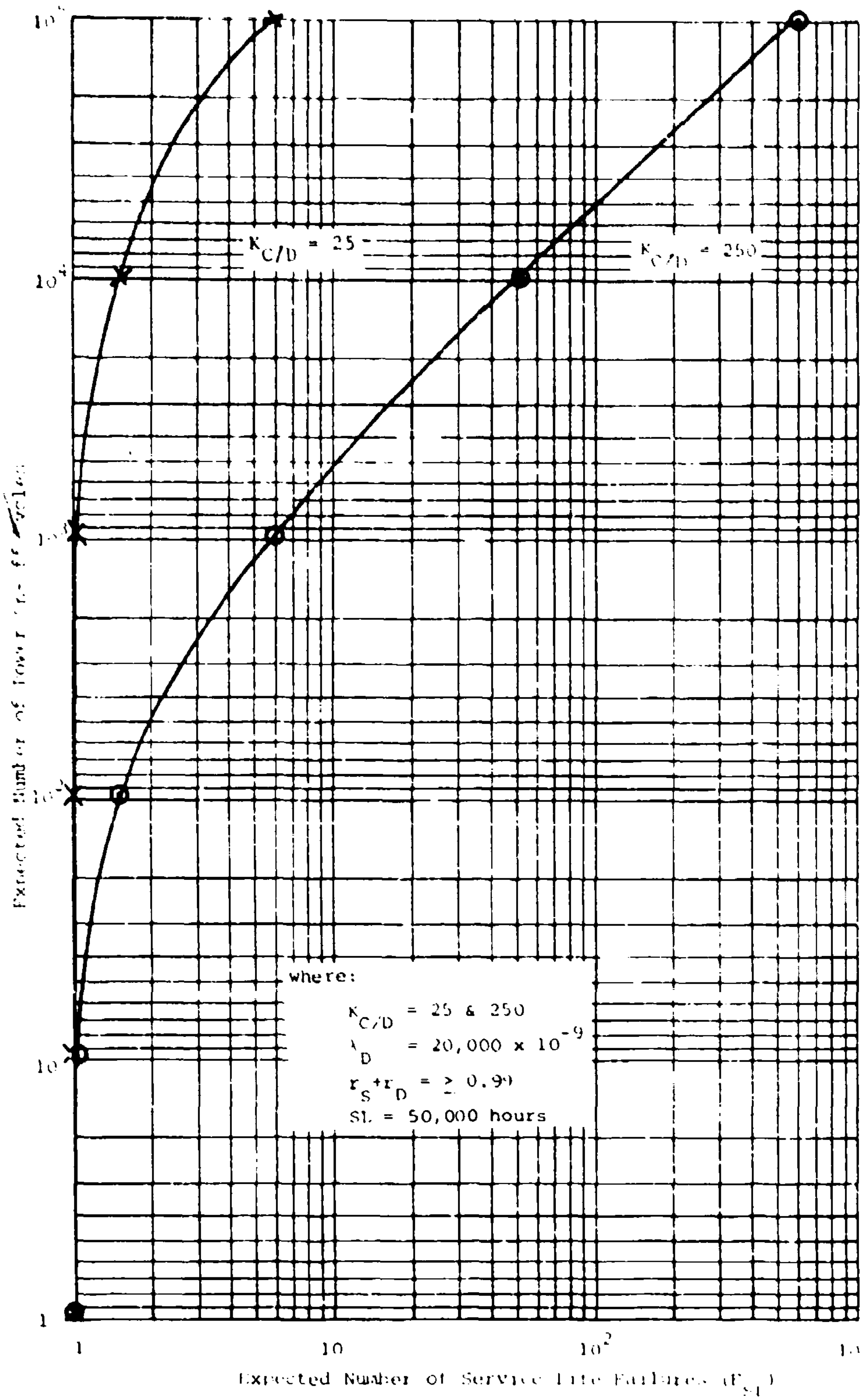


Figure 1.1.2-2 Relationship of Power On-Off Cycles To Service Life Failure **HYPOTHETICAL** High Reliability Electronic System

$$\lambda_{SL} \approx \left[1 + (375)\left(\frac{5}{730}\right)\right]\left[\frac{0.39}{10^9}\right]$$

$$\lambda_{SL} \approx \left[1 + 2.6\right]\left[\frac{0.39}{10^9}\right] = (3.6)\ 0.39 \times 10^{-9}$$

$\lambda_{SL} \approx$ <u>1.40 failures/10^9 hours</u> answer (uncorrected)

A correction for the 20% error can also be made:

$$\lambda_{SL} \approx (1.40)(1.20)$$

$\lambda_{SL} \approx$ <u>1.68 failures/10^9 hours</u> answer (corrected)

C. <u>Actual Apollo Experience</u>:

$$\lambda_{SL} = \frac{F_S + F_D + F_C + F_E}{t_{SL}}$$

where: F_S = 6 observed storage failures

F_D = not applicable = 0

F_C = 19 observed power on-off failures

F_E = 4 observed energized failures

t_{SL} = 15.8559 x 10^9 calendar part-hours

$$\lambda_{SL} = \frac{6 + 0 + 19 + 4}{15.8559 \times 10^9}$$

$$\lambda_{SL} = \frac{29}{15.8559 \times 10^9}$$

λ_{SL} = $\underline{1.83 \text{ failures}/10^9 \text{ hours}}$ answer.

For the above system in which a low rate of cycling was employed, the use of Equation 1.1.2-9 has been found to yield a good approximation. The limitations of its application to other electronic systems must be kept in mind; that is,

1. The test of $r_S + r_D \geq 0.99$ must be applied. When $r_S + r_D$ becomes less than 0.99, then Equation 1.1 2-8 (the full equation) must be employed.

2. The $K_{C/D}$ factor must be estimated based on similarity of part type, part quality, cyclic rate, energy rate and level, and transient suppression protection. Transient suppression protection is of prime importance as discussed in Sections 4.2.3 Apollo Data and 4.3.2 λ_C Factors herein.

2.0 SUMMARY

2.1 General

This report comprises the results of two 12-month programs conducted by Martin Marietta Aerospace. One program was conducted in order to collect, study, and analyze reliability information and data on dormant military electronic equipment and parts and to develop current dormant failure rates, factors, and prediction techniques. The purpose of the other program was to collect and analyze electronic equipment power on-off cycling data, to correlate failure incidence with power on-off cycling effects with respect to other energy states.

More than 276 billion part-hours of dormancy data have been collected on various part classes and categorized into three primary quality grades: Military Standard, high reliability, and ultimate reliability. Of the 276 billion part-hours, approximately 11 billion are on microelectronic devices. For the program concerned with power on-off cycling, about 118 billion part cycles of data have been collected on various part classes, primarily of high reliability grade.

The 276 billion part-hours of dormancy data contained in this report are new and in addition to that data collected for RADC-TR-67-307 (Reference 1). The dormancy failure rates for various part types and classes which were originally given in Reference 1 have been revised and updated in this report to reflect changes in technology and additional part-h urs of experience. The average dormant catastrophic failure rate for a high reliability part is 0.4 fits as compared to 3.1 fits for military standard electronic parts.

No testing was performed; therefore, no hardware was available for detailed failure mode and failure mechanism analysis. Martin Marietta, however, has several on-going programs under which current and detailed long life failure modes, failure mechanisms, design guidelines, potential problems, test methods, and process control requirements have been prepared. These data have been obtained and analyzed such that only information applicable to dormancy and power on-off cycling failure modes have been included in this report.

The 118 billion part-cycles of data are presented in tables by part class and type and part quality grade. Both cycle failure rate and cyclic ratio factor charts have been constructed and initially validated. Insufficient power on-off cycling data prevented inclusion of many part types. Quantitative relationships between cycling and dormancy and between cycling and the normally energized (operating) state have been developed and examples presented. Much more cycling information is required to complete the cyclic failure rate and ratio charts, and future programs should be directed to recording these data. Later analysis can then be done to update the initial cyclic tables.

During the data collection and analysis phases of these programs, definite interrelations between the dormancy, power on-off cycling, and normally energized states were found, developed, and verified. These interrelationships have been incorporated into service life equations and models. Both apply to military electronic equipment and utilize failure contributions from the dormancy and power on-off cycling states in combination with those of the normally energized state.

The basic interrelationships, terms, and equations are given in Equations 1.1.2-1 through 1.1.2-9. The full spectrum of service life models has been carefully developed, explained, and illustrated in Section 5.0 Reliability Models. The service life modeling techniques of Section 5.0 provide the means by which a system's reliability can be predicted or determined at any time during its service life cycle.

The study and investigation efforts of dormancy and power on-off cycling have been logically combined into this final technical report. This permits simultaneous retrieval of both sets of failure rates and interrelating factors from library sources. The logic and efficacy of a single report are also amplified by the fact that both studies have had the same ultimate goals:

1. The development and improvement in design, manufacturing, quality, and deployment techniques or conditions that promote attainment of maximum system reliability

2. The updating and upgrading of reliability predictions through improvements in military electronic system mathematical modeling methodology

3. The quantification of corresponding, viable, and authoritative failure rates and factors for dormancy and power on-off cycling from available field data.

2.2 Dormancy Program

A statistical analysis of the dormant and storage data collected during this program indicates that there is no significant difference between failure rates for equivalent part types in the storage and dormant modes. As a result of this finding, the dormant and storage data have been combined for all analyses. Because of the unavailability of drift failure rate information, only catastrophic failure rates and factors have been developed.

Dormancy data collected were primarily on three grades of electronic devices -- Military Standard, high reliability, and ultimate.

The data served to verify and strengthen the validity of the failure rates and factors originally developed in Reference 1. Many of the data gaps that previously existed have been filled, and changes in failure rates because of technological advances in design, manufacturing, and quality control are reflected. In almost all cases, the catastrophic failure rates have improved for individual electronic parts.

Analysis of the data shows that, on the average, dormant high reliability part failure rates are between 3 and 7 times better than the military standard grade. The ultimate grade part appears to be about 50 times better than the Military Standard grade; however, data are still insufficient to draw good or prove definite conclusions on this grade.

Based upon data from five systems with similar functions but with different vintages of designs and high reliability parts, dormant reliability growth trends have been determined. The growth trends indicate a steady improvement in average catastrophic dormant failure rates from 1964 to 1969. However, the rate of improvement has leveled off somewhat after 1967 and appears to be asymptotically approaching a level failure rate much more slowly after 1969. This failure rate improvement is primarily due to improved manufacturing control and more effective parts screening and burn-in.

Parametric drift information was sought on dormant devices, but has been found to be sparse. In general, however, parametric drift tests conducted on stored semiconductors have shown drift to be negligible on devices investigated. Positive drift trends have been observed on certain metal film and wirewound resistors. Even this drift rate does not indicate these types of resistors can be expected to go outside of end of life tolerances over a 10 year period. Insufficient drift data exist for other devices.

Because of the limited temperature and humidity ranges observed on the dormancy data, no pronounced differences in dormant catastrophic failure rates can be identified for temperature or humidity changes. Data from high temperature storage tests on microelectronic devices have been analyzed in a further attempt to correlate dormant failure rates with temperature. In general, the dormant failure rates increase with temperature, but the lack of more than two high temperature data points prevented the establishment of an Arrhenius curve and associated acceleration factors.

Quantification of relative environmental location factors for electronic systems has been accomplished for four dormant environments: satellite, in container in a controlled environment, not in container in a controlled environment, and submarine. The factors are listed in Tables 3.5.2-I and II.

Preliminary indications from failure mode data collected on approximately 100 electronic parts are that open and short failures occur with about equal frequency in the dormant state. However, a closer look at the data reveals that about 60 percent of the shorts experienced are due to contaminated integrated circuits. Without this failure mode, the opens are clearly in the majority.

Since the observed failure modes and mechanisms for dormancy are the same as those for the energized state, it can be concluded that dormancy itself is not the causative factor. Rather, device material properties or incipient defects are. Both types of these failure mechanisms can be correlated with dormant time as well as operating time. The rate at which failures occur in dormancy is lower because of zero or near zero electrical stresses applied.

Raw catastrophic dormant failure rate data on microelectronic devices were reviewed, analyzed, and rank ordered by Class A, B, or C device type per MIL-STD-883. Table 2.2-I is the final result of this effort. A catastrophic dormant failure rate chart (Table 2.2-II) was constructed for Military Standard and high reliability grade (or class) resistors and capacitors.

For semiconductors, diodes and transistors, a dormant catastrophic failure rate table was formed for Military Standard and tested extra (TX) categories of parts. Table 2.2-III depicts the final rank ordering.

Finally, a catastrophic dormant failure rate table (Table 2.2-IV) has been constructed for low population parts of Military Standard and high reliability grade from the raw data.

TABLE 2.2-I

Catastrophic Dormant Failure Rates (λ_D) for Microelectronic Devices

Catastrophic Dormant Failure Rates (Failures/Billion Part-Hours)	Military - Standard - 883		
	Class A	Class B	Class C
100.0			
70.0			Hybrid IC (Thin Film)
50.0			Hybrid IC (Thick Film)
30.0			
20.0		Hybrid IC (Thin Film)	Monolithic IC, Linear
15.0		Hybrid IC (Thick Film)	
10.0			
7.0		Monolithic IC, Linear	
5.0	Hybrid IC (Thin Film		Monolithic IC, Digital
3.0	Hybrid IC (Thick Film)		
2.0	Monolithic IC, Linear	Monolithic IC, Digital	
1.5			
1.0	Monolithic IC, Digital		

Class A - Devices intended for use where maintenance and replacement are extremely difficult or impossible, and reliability is imperative.

Class B - Devices intended for use where maintenance and replacement can be performed, but are difficult and expensive, and where reliability is imperative.

Class C - Devices intended for use where maintenance and replacement can be readily accomplished and down time is not a critical factor.

TABLE 2.2-II

Catastrophic Dormant Failure Rates (λ_D) for Resistors and Capacitors

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Resistors: Military Standard (MIL-STD)	Resistors: High Reliability (ER or Equivalent)	Capacitors: Military Standard (MIL-STD)	Capacitors: High Reliability (ER or Equivalent)
1000				
500				
200	Heaters			
100		Heaters	Tantalum, wet, slug	
70				
50	Variable carbon comp Variable wirewound Variable metal film		Aluminum Electrolytic	
30	Thermistors Varistors			
20			Variable ceramic (CV) Variable ceramic, tubular	Aluminum Electrolytic
15		Variable carbon comp Variable wirewound Variable metal film		
10		Thermistors Varistors	Variable air Variable trimmer, glass	Tantalum, wet, slug Variable ceramic (CV) Variable ceramic, tubular
7				
5	Carbon film		Tantalum, wet, foil	Variable air Variable trimmer, glass
3		Carbon film	Metalized mylar Metalized polycarbonate Metalized paper Foil, paper Foil, paper-mylar Mica	Tantalum, wet, foil

TABLE 2.2-II (Cont)

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Resistors		Capacitors	
	Military Standard (MIL-STD)	High Reliability (ER or Equivalent)	Military Standard (MIL-STD)	High Reliability (ER or Equivalent)
2	Wirewound, precision			Mica
1.5			Ceramic, general purpose	Metalized mylar Metalized polycarbonate Metalized paper Foil, paper Foil, paper-mylar
1	Wirewound, power	Wirewound, precision	Tantalum, solid Foil, mylar Foil, Polycarbonate Foil, Polystyrene	
0.7				Ceramic, general purpose
0.5		Wirewound, power		Tantalum, solid Foil, mylar Foil, polycarbonate Foil, polystyrene
0.3				
0.2	Metal film Tin oxide		Foil, teflon Ceramic, temperature compensating Procelain Glass	
0.15		Tin oxide		
0.1	Carbon composition	Metal film		Foil, teflon Ceramic, temperature compensating Porcelain Glass
0.07		Carbon composition		
0.05				
0.02				
0.01				

TABLE 2.2-III

Catastrophic Failure Rates (λ_D) for Semiconductors*

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Transistors: Military Standard (MIL-STD)	Transistors: High Reliability and TX	Diodes: Military Standard (MIL-STD)	Diodes: High Reliability and TX	
70					
50	Unijunction		Microwave diode		
30			Silicon controlled rectifier (SCR); Microdiode		
20	Field effect, (FET)	Unijunction			
15				Microwave diode	
10		Field effect, (FET)	Tunnel diode	Microdiode; Silicon controlled rectifier (SCR)	10.0
7			Varactor		
5	PNP			Tunnel diode	
3	NPN		Bridge, 4 diodes encapsulated	Varactor	
2					
1.5		PNP	Zener	Bridge, 4 diodes encapsulated	
1		NPN		Zener	1.0
0.7			Signal diode		
0.5					
0.3				Signal diode	
0.2					
0.15					
0.1					0.1

*All devices are silicon, Si

TABLE 2.2-IV

Catastrophic Dormant Failure Rates (λ_D) for Low Population Devices

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Military Standard (MIL-STD)	High Reliability	Military Standard (MIL-STD)	High Reliability	
1000.0	DC Torquers				1000
300.0	AC motor tachometer; Gyros	DC torquers	Stepping switch, telephone		
200.0	AC servos	AC motor tachometer; Gyros	Circuit breaker; Inertial switch, contactor; Thermostat, thermal switch; Humidity control switch; Incandescent lamp	Stepping switch, telephone	
100.0	Accelerometer	AC servos	Microswitch; Pressure switch; Primary battery, silver zinc	Circuit breaker; Inertial switch, contactor; Thermostat, thermal switch; Humidity control switch; Incandescent lamp	100
70.0		Accelerometer	Luminescent lamp		
50.0	DC power, motors; DC power, generators		Toggle switch; Quartz crystal, Frequency	Microswitch; Pressure switch; Primary battery, silver zinc	
30.0		DC power, motors; DC power, generators	Relay	Toggle switch; Quartz crystal, frequency; Luminescent lamp	
20.0	AC power, induction motor; AC power, synchronous motor; AC power, generators; Power transformer		Solar cell		
15.0				Relay	
10.0		AC power, induction motor; AC power, synchronous motor; AC power, generators; Power transformer		Solar cell	10.0
7.0					
5.0	RF transformers; RF chokes and coils; Audio transformer				
3.0	Inductors, reactors	RF transformers; RF chokes and coils; Audio transformer	Connectors		
2.0		Inductors, reactors		Connectors	
1.5					
0.1					0.1
0.05					
0.03	Magnetic memory core		Solder connection		
0.02		Magnetic memory core	Connector pin, male or socket		
0.01				Solder connection	
0.01				Connector pin, male or socket	0.01

2.3 Power On-Off Cycling Program

The results of the data collection and analysis program indicate that power on-off cycling can have a definite adverse effect upon electronic equipment reliability. The degree to which reliability is affected depends upon several factors such as part quality, cyclic rate, temperature effects, environment, and transient suppression capabilities of the system. The degree of degradation can be controlled or greatly minimized by careful design and stringent manufacturing control. These factors are not always independent of one another, but rather depend upon system design and duty cycle characteristics. Therefore, great caution and care must be exercised in construction of any power on-off cycling mathematical model and development of quantitative values for factors in the model.

This report is considered to be the initial step toward defining the terms and factors related to power cycling and developing the necessary mathematical models and quantitative factors required for reliability prediction purposes. It should be recognized that this is only a starting point with more and better power on-off cycling data required before a high degree of confidence can be obtained in the prediction methods and values. However, with the partial verification of the models and factors afforded by the on-off cycling data collected, it appears that there is a reasonable validity in the approach taken in this report.

Based upon the data collected, a power cycling failure rate model to estimate the cyclic failure rate (λ_C) has been developed and is given in Equations 2.3.1-1 and -2. The model identifies, defines, and correlates the factors exerting primary influences on cycling failures: part quality, cyclic rate, temperature effects, environment, and transient suppression characteristics of the equipment.

The temperature factor exerts a major influence over the model because of the large percentage (about 90 percent) of observed part failures which appear to be related to expansion and contraction resulting from temperature change. These factors can range from 1 to greater than 200. Further quantification of this important factor should be obtained by properly designed experiments in which certain critical influence factors would be varied while others would be held constant.

In this initial modeling attempt, the contributing factors of λ_C have been reviewed. The dependent ones were determined and grouped into a single C_i factor.

As a result, only the basic cyclic failure rate and five modifying factors remain. The initial λ_C model, its terms, and derivation are:

$$\lambda_C = \lambda_{CB} \prod_{i=1}^{n=5} C_i \qquad \text{(Equation 2.3.1-1)}$$

or

$$\lambda_C = \lambda_{CB} C_Q C_{N_C} C_T C_{TS} C_E \qquad \text{(Equation 2.3.1-2)}$$

where λ_C = field cyclic failure rate of part, component or system

λ_{CB} = base cyclic failure rate as related to initial temperature state

C_Q = part quality (grade or class) factor; this factor is a function of the manufacturing process and subsequent controls imposed such as Group A and B electrical tests, special screens, or burn-in on individual parts and components.

C_{N_C} = cycling rate factor; this factor is a function of the expected cycling rate (normally expressed as cycles per hour); the cycling rate can be estimated for a given system as:

$$N_C = \frac{N}{t_{SL}}$$

that is, the total number of actual or anticipated power on-off cycles that will occur on that item during its entire service life expressed in hours. This factor represents all non-temperature related effects such as mechanical shock, wear, vibration, material fatigue, creep, or other cyclic induced stresses.

C_T = temperature effect factor; this is a complex factor comprised of several sub-factors which are dependent:

1 Initial temperature state

2 Applied electrical energy versus part derating with resultant thermal stresses

3 Thermal lags at turn-on and at turn-off

4 Temperature stabilization state (time to and time at)

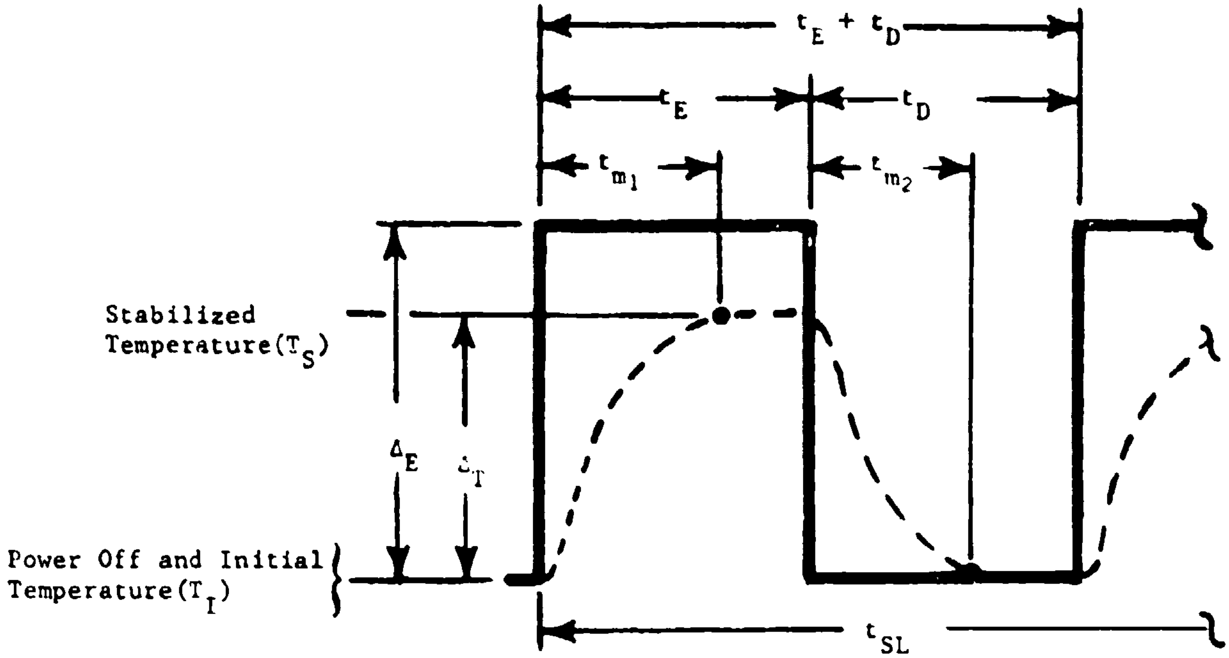
5 Residual temperature effects (a function of time between cycles).

Refer to Figure 2.3-1 and related discussion for a more detailed explanation.

C_{TS} = transient suppression factor; this factor is a function of the degree to which transient suppression circuitry and design have been provided to eliminate or reduce damaging voltage or current transients at power turn-on or turn-off. These transients may either be line conducted or induced by internal or external sources.

C_E = environmental mode factor; this factor is an adjustment factor for the various environments in which power on-off cycling occurs.

The subfactors of C_T are sometimes dependent and sometimes independent of one another. This can be better understood by studying Figure 2.3-1. This figure shows the initial temperatures state (T_I) as room ambient in the power-off condition. When the power is turned on, the internal temperature rises at a rate dependent on applied power, part derating and packaging, etc. The temperature rises until it reaches a stabilized temperature (T_S) at time t_{m_1} providing that $t_{m_1} \geq t_E$. When power is turned off, the internal temperature decreases at a rate dependent on heat dissipation paths. The temperature decreases until it again reaches room ambient at time t_{m_1} providing $t_{m_2} \leq t_D$. The terms t_{m_1} and t_{m_2} are thermal lag times and their values are contingent upon energy levels, part derating, equipment configuration (density, heat sinks, construction, etc.), and ancillary cooling. The interdependency of the C_T factor contributors can now be readily seen.



NOTES:

——— Energy Profile for Power On-Off Cycle

- - - Temperature Profile for Power On-Off Cycle

Δ_E = Energy Change (Power Off to Power On or Vice Versa)

$\Delta_T = T_S - T_I$ = Maximum Temperature Change

If $t_{m_1} \geq t_E$, then full Δ_T is not realized and this reduces temperature effect.

If $t_{m_2} \geq t_D$, then residual temperature effects increase temperature effect.

Figure 2.3-1 General Diagram of Contributors to the Temperature Effect Factor C_T During Power On-Off Cycling

The raw power on-off cycling data have been used to derive preliminary quality improvement factors, C_Q values for the power on-off cycling environment. These values are shown in Table 2.3-I and relate to the amount of improvement which can be expected in going from Military Standard to high reliability quality levels.

For example, the cycling failure rate of a high reliability type integrated circuit is expected to be 1/14,800 that of a comparable Military Standard device. The overall factor for electronic parts appears to be about 1/3,300. In studying the table, it can be observed that screening and burn-in on integrated circuits and transistors are much more effective in removing parts with inherent weakness to cycling effects than is the case with resistors, diodes and magnetics. Temperature cycling is well known to be a beneficial screen for microelectronics and transistors. The reason for this efficiency can be related to the thermal environment which is a major contributor to power on-off cycling failures.

TABLE 2.3-I

Estimated Values of C_Q for Various Part Types

Part Type	C_Q Military Standard to High Reliability*
Integrated circuits	14,800 to 1
Transistors	4,200 to 1
Capacitors	1,500 to 1
Resistors	700 to 1
Diodes	500 to 1
Inductive devices	100 to 1
Average C_Q (total experience)	3,300 to 1

*Normalized to high reliability value for same part type

Another factor for λ_C is C_E. Almost all the usable data collected and analyzed came from laboratory conditions. This fact precluded determining C_E values from the power on-off cycling data; instead, C_E values have been derived from energized experience and assumed to be applicable to power on-off cycling. Table 2.3-II presents the C_E values for various environments.

TABLE 2.3-II

Estimated Values of C_E for Various Environments

(These modifiers apply only to the cyclic part failure rate. If an overall part failure rate including dormancy and operating is to be determined, then caution must be exercised not to double count environmental effects.)

Environment	C_E
Satellite	0.1
Laboratory	1.0
Ground, Fixed	5.0
Ground, Mobile	7.5
Aircraft, Manned	6.5
Aircraft, Unmanned	15.0
Missile, Checkout	5.0
Missile, Flight	25.0
Missile, Ground Launch*	50 - 100*
Missile, Airborne Launch*	100 - 1000*
Shipboard, Surface	-
Shipboard, Submarine	10.0

* These C_E values apply only to the first few seconds of missile launch. Missile flight C_E then becomes 25.0.

In addition to the cyclic failure rate model, **laboratory cyclic** failure rates and a failure rate table (Tables 2.3-III and 2.3-IV) have been constructed. The former table is on microelectronic devices and the latter on high reliability parts. Both tables apply only to electronic systems in a laboratory environment, having a cyclic rate of 6 cycles or less per 24 hours, having the cycle on time one hour or longer, having the time between cycles one hour or longer, having an average part derating of 50 percent or greater, and having transient suppression circuitry designed in the equipment.

The service life model (Refer to Section 5.0 Reliability Models) which has been developed reflects the effects of power on-off cycling on equipment reliability along with the other service life conditions usually experienced by equipments: dormancy and the fully energized state. The model adds a new dimension to trade-off studies involving periodic testing. Without the effects of cycling taken into account, reliability predictions can be overly optimistic. Of course the degree of optimism is dependent upon the cyclic rate and related cyclic characteristics. In addition, the service life model is a valuable tool for determining logistics requirements. More accurate failure data on specific part types and quantities can be obtained as a result of including cyclic failure rates.

The incidence of power on-off cycling has been correlated to other states such as dormancy and normally energized. This correlation is in the form of ratios of the cyclic failure rates to those of dormancy and energized. Table 2.3-V is the first such attempt at developing and ranking these factors. By the use of these factors, it is now possible to estimate how much more stressful the cyclic state is when compared to the dormant state for similar electronic devices in identical power on-off cycling conditions. Analysis of this data indicates that on the system level a single power on-off cycle is between 1 and 375 times more stressful or effective in causing failures than one hour of dormant time. This wide range demonstrates just how great an effect cycling can have on equipment reliability. In contrast to this, the ratio of energized to dormant failure rate was between 40 and 100, depending upon the part and component mix within the system.

Correlation of power on-off cycling failure incidence with environmental application or with equipment type was thwarted. This was due to the fact that almost all of the validated power turn-on and power turn-off failures came from missile electronic systems in a laboratory environment.

TABLE 2.3-III

Catastrophic Cyclic Failure Rates (λ_C) For Microelectronic Devices

1. Environment - equipment laboratory operation & satellite
2. Cyclic Rate - 6 cycles (or less) per 24 hours
3. Time On - sufficient for temperature stabilization
4. Derating - 50 percent or greater on voltage

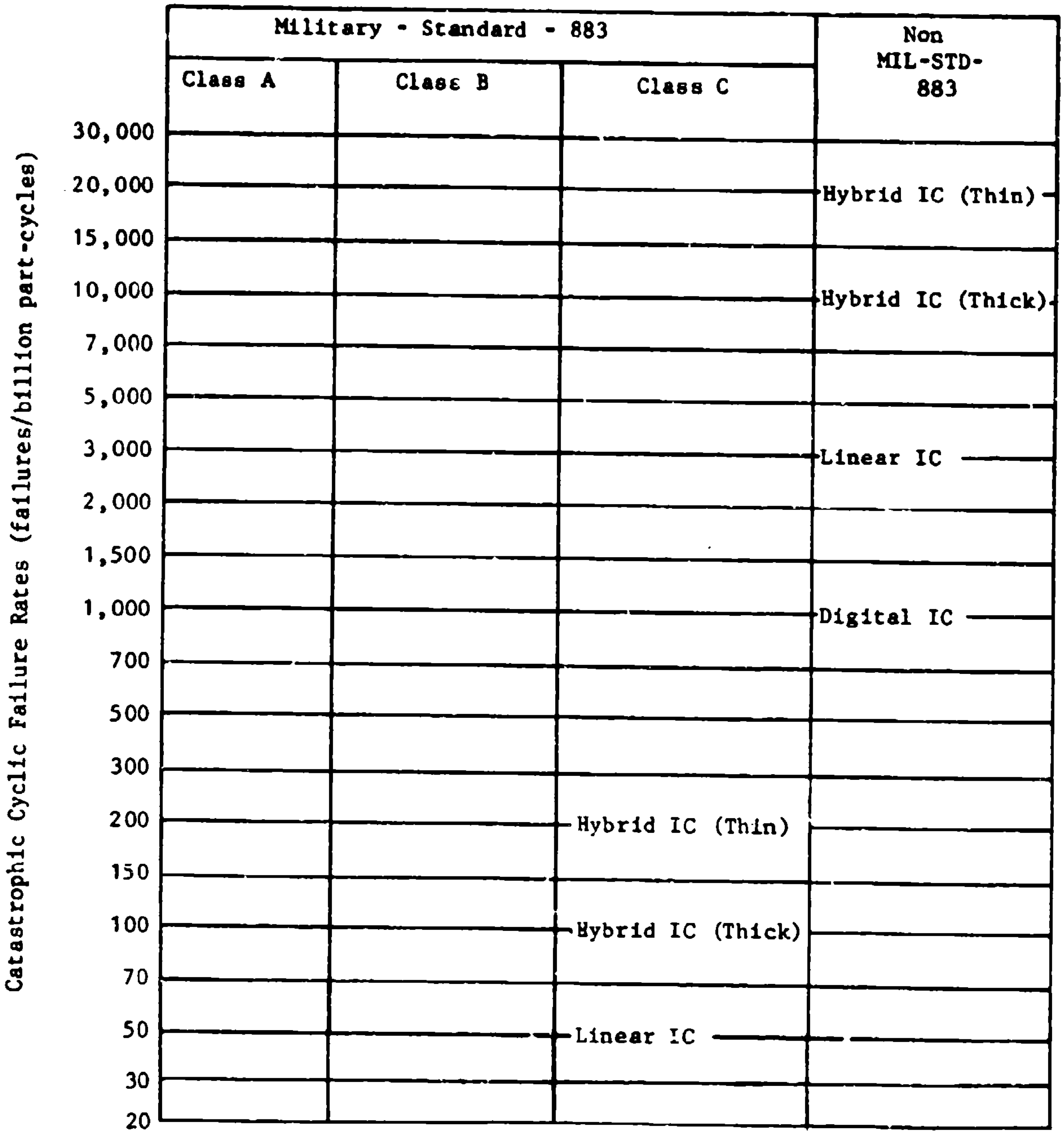


TABLE 2.3-III
(continued)

Catastrophic Cyclic Failure Rates (failures/billion part-cycles)				
15.0			Digital IC	
10.0				
7.0				
5.0				
3.0				
2.0				
1.5				
1.0				
0.70				
0.50				
0.30		Hybrid IC (Thin)		
0.20		Hybrid IC (Thick)		
0.15				
0.10				
0.070	Hybrid IC (Thin)	Linear IC		
0.050	Hybrid IC (Thick)			
0.030	Linear IC	Digital IC		
0.020				
0.015	Digital IC			
0.010				

Class A - Devices intended for use where maintenance and replacement are extremely difficult or impossible, and reliability is imperative.

Class B - Devices intended for use where maintenance and replacement can be performed, but are difficult and expensive, and where reliability is imperative.

Class C - Devices intended for use where maintenance and replacement can be readily accomplished and down time is not a critical factor.

Non MIL-STD-883 - Devices are not intended for military application, but data has been included for information purposes only.

TABLE 2.3-IV

Catastrophic Cyclic Failure Rates (λ_C) For High Reliability Parts and Components*

1. Environment - **equipment laboratory operation & satellite**
2. Cyclic rate - 6 cycles (or less) per 24 hours
3. Time on - sufficient for temperature stabilization
4. Derating - 50 percent or greater on electronic devices

Catastrophic Cyclic Failure Rate (failures/billion part-cycles)

Rate	Parts and Components	Rate	Parts and Components
50.00	Transformers	500000	
20.00		200000	
10.00	Transistors, silicon, (high power)	100000	
5.00		50000	
3.00		30000	
2.00		20000	Motors, Switches
1.00		10000	Lamps, incandescent
0.50	Transistors, silicon (medium power)	5000	Crystals
0.30		3000	
0.20		2000	Lamps, electroluminescent
0.10	Transistors, silicon, (low power); Capacitors	1000	Relays; Capacitors, mylar
0.05	Diodes	500	
0.03	Resistors	300	
0.02		200	Light emitting diodes (LED)
0.01		100	Capacitor, tantalum, solid

*Note: An estimate of λ_C values for Military Standard parts and components under similar environmental, cyclic rate, duty cycle, and derating conditions can be made by applying the appropriate C_Q values of Table 2.3-I to the values shown in this Table.

TABLE 2.3-V

$K_{C/D}$ Ratios for High Reliability Parts and Compo

1. Environment - equipment laboratory operation
2. Cyclic rate - 6 cycles (or less) per 24 hours
3. Time on - sufficient for temperature stabil
4. Derating - 50 percent or greater on devices

Cyclic Failure Rate Ratio for $K_{C/D}$ In Hours/Cycle

	Resistors and Resistive Devices 1	Capacitors 2	Semiconductors and Microelectronic Devices 3	Transformers and Inductors 4
2000				
1000				Transformers
500			Hybrid IC (thin film)	
200		Tantalum, wet, foil Tantalum, wet, slug	High power transistor Hybrid IC (thick film)	
100	Heaters Thermostats Thermistors Temperature sensing	Tantalum, solid Mylar	High power diode	R.F. chokes and coils
50	Variable Wirewound	Polystyrene Metal film	Zener diode Light emitting diode Monolithic IC, linear	Reactors and inductors Magnetic memory cores
20	Carbon Film		Monolithic IC, digital Medium power transistor	
10	Metal film Tin oxide	Glass Ceramic	Low power transistor Medium power diode	
5	Carbon composition		Low power diode	
2				
1				

TABLE 2.3-V

PD Ratios for High Reliability Parts and Components*

avironment - equipment laboratory operation
yclic rate - 6 cycles (or less) per 24 hours
ime on - sufficient for temperature stabilization
erating - 50 percent or greater on devices in columns 1, 2, and 3

Semiconductors and Microelectronic Devices 3	Transformers and Inductors 4	Electromechanical and Rotating Devices 5	Electrical 6	
				2000
	Transformers			1000
orid IC (thin film)		Switches		500
;h power transistor orid IC (thick film)		Relays Servo motors		200
;h power diode	R.F. chokes and coils	Resolvers Torquer motors Blower motors	Lamps, incandescent Lamps, electrolumines Fuses	100
er diode ht emitting diode olithic IC, linear	Reactors and inductors Magnetic memory cores	Gyros, integrating Counters Slip rings	Lamps, annunciator	50
olithic IC, digital ium power transistor		Pulsed integrating pendulum	Couplings** Connectors** Connector pins**	20
power transistor ium power diode				10
power diode				5
				2
				1

**Per connection

Available failure mode and mechanism data indicate an overwhelming tendency of power on-off cycling to induce failures in the open mode. Approximately 90 percent of the failures analyzed were opens. The reason for this high percentage can be attributed to expansion and contraction effects which take place when devices are energized and de-energized. Improper welds, defective solder joints, nicked fine wire, and marginal structural assemblies can fail when subjected to this environment. In many cases the malfunctions which occurred can be tied back to improper process control during manufacturing, a situation which may never be completely corrected.

Power on-off cycling appears to be particularly effective in precipitating poor conductivity fault points in a system. This is illustrated by on-off cycling failures detected in transformers with opens, breaks, fractures, or bad solder joints; in switches with poor solder joints; in capacitors with bad internal welds and solder joints; and in a tachometer-generator with a poor solder connection. Although thermal cycling is often used as a screen to detect defects such as those described for transformers, it is possible that power cycling represents a better way to identify potential malfunctions of this type. The reason for this is that power cycling can induce local hot spot heating at the area where the defect exists. The failure will then become apparent after a period of expansion and contraction caused by the power cycling.

3.0 DORMANCY FAILURE RATES AND FACTORS

3.1 Introduction

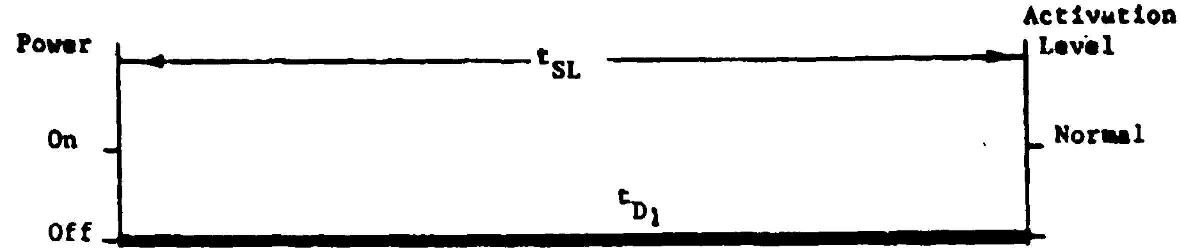
The purpose and intent of the Dormancy Program has been the collection, study, and analysis of electronic equipment reliability information and data related to actual dormant conditions. These data have been used to supplement and update Reference 1, including development of a prediction method for electronic equipment in a dormant state and of quantifying dormant failure rates and factors for use in the prediction model. No testing of electronic items has been done to obtain data, but rather an extensive data survey and collection effort was undertaken to locate and obtain necessary data.

The equipment studied was typical of those used to perform electronic functions in military ground, airborne, missile, missile shipboard, and satellite applications. Special emphasis was given to the area of microelectronics. In addition, some data on electrical, electromechanical, and nonelectronic devices were available and have been included, but no special effort was made for these categories.

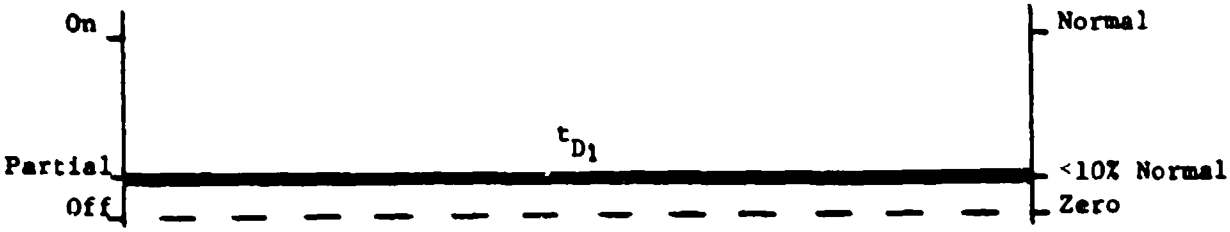
Dormancy is the state wherein a device or equipment is connected to a system in the normal operational configuration and experiences below normal or periodic electrical and environmental stresses for prolonged periods (up to five years or more) before being used in a mission. Below normal electrical stresses are considered, for the purposes of this study, to range from less than 10 percent of the normal activation (operational) level down to and including the zero activation level (no electrical stress). Figure 3.1-1 illustrates typical states of dormancy, and the time spans associated with dormancy are indicated by t_{D_1}, t_{D_2}, t_{D_3}, etc.

The scope of this study also has been:

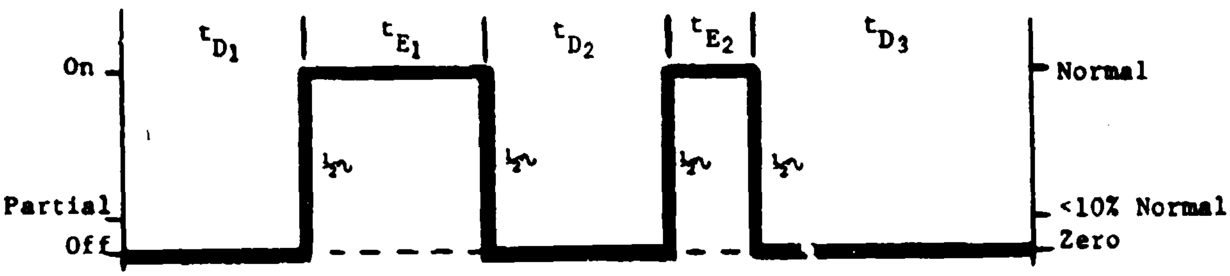
1 To include effects of temperature and humidity as well as any other environmental stress that may affect reliability



Example 1 Dormant Mode - No power



Example 2 Dormant Mode - <10% Power Applied



Example 3 Dormant Mode - With Aperiodic Cycles With Either No Power or <10% Normal Power Applied During Dormancy

NOTE: Symbols are defined in Section 8.0 herein.

Figure 3.1-1 Typical Dormancy Modes (Idealized)

2. To develop device failure rate and failure mode information as a function of dormant operating time and stresses

3. To develop a capability for predicting the reliability of an electronic system subject to given conditions of dormant operation

4. To develop a capability for selecting the specific conditions of dormant operation which promote attainment of maximum system reliability.

This dormancy study and investigation has shown that during periods of dormancy the reliability of military electronic equipment is affected. Preliminary mathematical models have been developed to quantify this effect. Corresponding dormant failure rate data, factors, and terminology have been developed for use in the models. Analyses have been performed on the data to determine average system failure rates, various environmental and improvement factors, and dormant system reliability growth curves. To the greatest extent possible, failure analysis results have been sought on field information related to dormancy. These analyses have been summarized in a discussion on failure modes and mechanisms. A summary of the total quantity of data collected is shown in Table 3.1-I.

There are areas remaining in which the need exists for additional data in order to better estimate or validate failure rates. The primary need is for data on state-of-the-art integrated circuits such as Medium Scale Integration (MSI) and Large Scale Integration (LSI) devices. These new technology part types had not been used in the dormant systems from which data were available for this study. Most systems of any complexity utilizing advanced designs involving MSI, LSI, and hybrids are either still in the design stages or have not been in the field long enough to accumulate a quantity of data sufficient to permit the calculation of best estimate failure rates.

3.2 Previous Work

A previous RADC study was conducted to determine the effects of dormant operating and storage conditions on electronic equipment and parts. This study culminated in July, 1967, with report RADC-TR-67-307 (Reference 1) which contained over 760 billion part-hours of experience. Failure rates were given for all major electrical part types and information on failure modes and mechanisms was included. Modeling techniques

TABLE 3.1-I

Summary of Dormancy Data Collected

Part Classification	Part-Hours of Raw Data $(\times 10^9)$
Military Standard	54.515
High reliability	205.463
Ultimate	16.550
Total	276.528

were developed to show the methods by which realistic weapon system decisions can bo made to obtain maximum nonoperating survivability. The data and parts contained in this study are from 8 to 15 years old and can be considered obsolete with the advances in the state-of-the-art in microelectronics and advanced semiconductor devices.

3.3 Part Classes and Failure Rates

Most sources of the data collected for this contract reported only catastrophic failures. The few cases in which drift failures were reported were insufficient to allow calculation of drift failure rates so drift failures and failure rates have not been included in the study.

Brownlee's test (see Appendix A and Reference 15) was used to test sources within part-classes for consistency wherever sufficient data were available. The only serious anomaly discovered concerned a single source, and involved slightly over 2 billion part-hours of data on Military Standard transistors. The failure rate for this data was significantly better (Brownlee's test conducted at 5 percent level) than that for other sources involving the same part type and quality. In fact, the failure rates from this source were slightly better than those in the high reliability part class. The slightly over 2 billion part-hours involved were deleted from the study. Table 3.3.2-I reflects this deletion.

There are three primary grades of parts referred to in this report: Military Standard, high reliability, and ultimate. A brief description of the tests associated with each grade is given in Table 3.3-I. The high reliability grade is most similar to the select military standard type referred to in RADC-TR-67-307 (Reference 1). For integrated circuits, MIL-STD-883 Class "C" is considered to be Military Standard and MIL-STD-883 Classes "A" and "B" are high reliability. Only one source was classified in the ultimate grade, the BTL submarine cable repeaters. As a minimum, these parts receive a 6 month burn-in. A complete description of the production controls and screening programs for these devices is given in Reference 2.

3.3.1 Commercial Part Class

No data were available on parts of this class.

TABLE 3.3-I

Description of Electronic Part Classifications

Part Classification	Associated Testing and Screening	Typical Using Project
1 Military Standard	Group A Environmental Proof Tests Group B Electrical Tests	Pershing
2 High Reliability	Class 1, Selected Vendor, Serializing, 100% Receiving Inspection, 100% Burn-in	SPRINT Minuteman II & III
3 Ultimate	Class 2, 100% Extended Burn-in, Parameter Drift Screening, Stringent Quality Inspections	Bell System Undersea Cable Repeaters

3.3.2 Military Standard Part Class

Over 54 billion part hours of experience and 167 catastrophic failures were collected for this part class. This was sufficient to allow calculation of best estimates of failure rates for high usage parts. Additional experience is still needed for calculation of failure rates for low usage parts.

Military Standard 883, Class C integrated circuits were included in this class of parts.

These data are presented in Table 3.3.2-I.

3.3.3 High Reliability Part Class

Over 205 billion part hours of experience and 84 failures were collected for this part class. Failure rates were calculated for many high usage parts, but additional experience is needed to establish failure rates for remaining categories.

Military Standard 883 Class A and Class B integrated circuits were included in this class.

These data are presented in Table 3.3.3-I.

3.3.4 Ultimate Reliability Parts

Bell Telephone Laboratories contributed 16.5 billion part hours of data on components intended for use in undersea cables. These parts were subjected to extremely rigorous screening techniques including a 4500 hour burn-in. Comparison of this data with that of the high reliability part class indicated that the Bell data had a considerably lower failure rate and, therefore, should be segregated.

No failures were observed for these data; therefore, best estimates of the upper failure rate limit were calculated assuming one failure. These have been included in this report as an indication of the part reliability which can be obtained if screening procedures approaching the ultimate are utilized.

These data are presented in Table 3.3.4-I.

TABLE 3.3.2-I

Observed Dormancy Failure Data, Military Standard Parts

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Antennas and Peripheral Equip.	4.260	0	<234.74
Antennas	0.610	0	<1639.34
Attenuators	0.610	0	<1639.34
Circulators, Four Port	1.010	0	<990.10
Couplers, Antenna	1.220	0	<819.67
Couplers, Directional	0.810	0	<1234.57
Capacitors	10876.852	18	1.65
General Class	9406.075	11	1.17
Ceramic	729.386	3	4.11
Chip	18.301	0	<54.64
Glass	4.554	0	<219.59
Metalized Paper	329.000	2	6.08
Mica	296.573	0	<3.37
Mylar	0.109	0	<9174.31
Tantalum, Foil	7.698	0	<129.90
Tantalum, Slug, Wet	0.843	2	2372.48
Variable, Trimmer, Piston	84.313	0	<11.86
Filters	26.586	1	37.61
Ceramic, Bandpass	0.126	0	<7936.51
Ceramic, Feed-Through	0.378	1	2645.50
Transmittal	0.378	0	<2645.50
RC, Low Pass	25.704	0	<38.90
Flight Instruments, Missile	264.000	25	94.70
Fuses	1.500	0	<666.67

TABLE 3.3.2-I
(continued)

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Inductive Devices	6.174	0	<161.97
Chokes	0.756	0	<1322.75
Coils, RF	5.418	0	<184.57
Inertial Guidance Devices	1.008	0	<992.06
Accelerometers	0.378	0	<2645.50
Angular	0.252	0	<3968.25
Linear	0.126	0	<7936.51
Gyros, Rate	0.630	0	<1587.30
Microwave Devices, Isolator	0.126	0	<7936.00
Relays	472.000	18	38.14
Resistors	31992.482	17	0.53
General Class	23097.618	11	0.48
Carbon Composition	4652.000	0	<0.21
Carbon Film	6.134	0	<163.03
Metal Film	3290.034	0	<0.30
Thermistor	95.284	3	31.48
Wirewound	840.846	2	2.38
General Class	135.547	0	<7.38
Power	376.299	2	5.31
Precision	329.000	0	<3.04
Variable	10.566	1	94.64
Semiconductors	10351.900	65	6.28
Diodes	6871.000	41	5.97
General Class	6036.000	41	6.79
Low Power	228.000	0	<4.39
Zener	607.000	0	<1.65
Integrated Circuits, Class C	1952.900	8	4.10
Digital	1952.900	8	4.10
Transistors, Silicon	1528.000	16	10.47
Surge Arrestors, Sparkgap	7.290	0	<137.17
Transformers	509.000	9	17.68
Tubes	1.017	14	13765.98
Valves, Hydraulic, Servo	0.756	0	<1322.75
Total	54,514.951	167	3.06

TABLE 3.3.3-I

Observed Dormancy Failure Data, High Reliability Parts

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Batteries, Silver-Zinc	0.200	0	<5000.00
Capacitors	13295.384	15	1.13
General Class	4165.800	2	0.48
Aluminum Electrolytic	6.080	0	<164.47
Ceramic	3103.041	2	0.64
Feed Through	11.551	0	<86.57
Glass	294.843	0	<3.39
Metallic Film	2.200	0	<454.55
Mica	354.207	1	2.82
Mica, Dipped	8.820	0	<113.38
Mica, Reconstituted	0.410	0	<2439.02
Paper	18.645	0	<53.63
Plastic	30.222	1	33.09
Polycarbon Film	23.728	1	42.14
Polystyrene	9.500	0	<105.26
Tantalum, Gen Class	2612.092	2	0.77
Tantalum, Foil	144.782	0	<6.91
Tantalum, Solid	2029.836	1	0.49
Tantalum, Wet	430.093	4	9.30
Teflon	0.376	0	<2659.57
Variable, Air	40.630	1	24.61
Variable, Ceramic	0.322	0	<3105.59
Variable, Glass	8.206	0	<121.86
Connective Devices	91158.575	1	0.01
Connectors	800.975	1	1.25
Pins	55437.600	0	<0.02
Soldered Connections	34920.000	0	<0.03
Crystals	20.065	0	<49.84
Electromechanical Devices	23.720	0	<42.16
Counters	1.400	0	<714.29
Fans	1.020	0	<980.39
Axial	0.610	0	<1639.34
Centrifugal	0.410	0	<2439.02
Motors	6.600	0	<151.52
Blower	1.500	0	<666.70

TABLE 3.3.3-I
(continued)

Part Type	t_D Part-Hours ($\times 10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
DC	0.200	0	<5000.00
Servo	1.900	0	<526.32
Torque	3.000	0	<333.33
Resolvers	8.800	0	<113.64
Slip Rings	5.900	0	<169.49
Filters	98.532	0	<10.15
General Class	88.488	0	<11.30
EMI	10.044	0	<99.56
Fuses	1.500	0	<666.67
Heaters	1.900	0	<526.32
Inductive Devices	655.527	0	<1.53
Chokes	9.437	0	<105.97
Coils	364.981	0	<2.74
General Class	79.181	0	<12.63
Radio Frequency	285.800	0	<3.50
Delay Lines	0.752	0	<1329.79
Inductors	261.557	0	<3.82
Reactors	18.800	0	<53.19
Inertial Guidance Devices	5.220	8	1532.57
Accelerometers	2.610	6	2298.85
General Class	0.410	0	<2439.02
Pulsed Integrating Pendulum	2.200	6	2727.27
Gyros	2.610	2	766.28
General Class	0.410	0	<2439.02
Inertial Reference, Integrating	2.200	2	909.09
Lamps	37.500	2	53.33
Annunciator	0.700	0	<1428.27
Electroluminescent	27.300	1	36.63
Incandescent	9.500	1	105.26
Oscillator / Isolator	0.200	0	<5000.00
Magnetic Cores	24771.000	0	<0.04
Relays	567.905	10	17.61

TABLE 3.3.3-I
(continued)

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Resistors	32518.917	2	0.06
General Class	4757.200	0	<0.21
Carbon Composition	6896.740	0	<0.14
Carbon Film	107.934	0	<9.26
Metal Film	12533.498	1	0.08
Thermal	1.925	0	<519.48
Thermistor	4.578	0	<218.44
Tin Oxide	4655.400	0	<0.21
Wirewound	3499.183	0	<0.29
General	601.582	0	<1.67
Power	2108.571	0	<0.47
Precision	788.020	0	<1.27
Heater Element	1.010	0	<990.10
Variable	62.459	1	16.01
General Class	36.898	0	<27.10
Film	23.300	1	42.92
Plastic	0.756	0	<1322.75
Wirewound	1.505	0	<664.45
Semiconductors	38573.832	33	0.86
Diodes	18761.312	7	0.37
General Class	9415.329	3	0.32
Low Power	7605.035	3	0.39
Medium Power	694.435	0	<1.44
High Power	133.321	0	<7.50
Micro	11.364	0	<88.00
Tunnel	1.912	0	<523.01
Varactor	1.913	0	<522.74
Zener	898.003	1	1.11
Integrated Circuits	9027.236	14	1.55
Class A	5863.736	6	1.02
Digital	5328.202	5	0.94
Linear	535.534	1	1.87
Class B	3120.254	7	2.24
General Class	615.000	0	<1.63
Digital	2269.720	5	2.20
Linear	235.534	2	8.49
Hybrid Class B (thin film)	43.246	1	23.12
Silicon Controlled Rectifiers	57.606	0	<17.36

TABLE 3.3.3-I
(continued)

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Transistors, Silicon	10662.041	12	1.13
General Class	3146.791	3	0.95
Low Power	5482.804	6	1.09
General Category	1761.401	1	0.57
NPN	3035.643	4	1.32
PNP	685.760	1	1.46
Medium Power	523.933	0	<1.91
General Class	86.000	0	<11.63
NPN	249.326	0	<4.01
PNP	188.607	0	<5.30
High Power	1435.810	3	2.09
General Class	192.663	1	5.19
NPN	791.156	2	2.53
PNP	451.991	0	<2.21
Field Effect	71.674	0	<13.95
Unijunction	1.027	0	<973.71
Transistors, Germanium	65.637	0	<15.24
Low Power, NPN	20.834	0	<48.00
Low Power, PNP	44.803	0	<22.32
Solar Cells	748.583	8	10.69
Switches	50.951	2	39.25
General Class	32.100	0	<31.15
Electronic	1.220	0	<819.67
Humidity Control	0.410	0	<2439.02
Indicator Light	1.220	0	<819.67
Inertial	0.410	0	<2439.02
Micro	4.226	0	<236.63
Pressure	0.610	0	<1639.34
RF	0.956	0	<1046.03
RF,Ferrite	0.139	0	<7194.24
Stepping	5.000	2	400.00
Thermostatic	3.650	0	<273.97
Toggle	1.010	0	<990.10
Temperature Sensors	0.200	0	<5000.00
Thermostats	3.724	0	<268.53
Transformers	2928.309	3	1.02
General Class	1987.016	1	0.50

TABLE 3.3.3-I
(continued)

Part Type	t_D Part-Hours ($\times 10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Audio Frequency	632.810	2	3.16
High Voltage	6.651	0	<150.34
Low Voltage	1.319	0	<758.15
Power	83.028	0	<12.04
Pulse	9.514	0	<105.11
Radio Frequency	207.771	0	<4.81
Saturable	0.200	0	<5000.00
Tubes, Sprytron	0.410	0	<2439.02
Video Signal Detectors	0.610	0	<1639.34
Total	205,462.764	84	0.41

TABLE 3.3.4-I

Observed Dormancy Failure Data, Ultimate Reliability Parts

Part Type	t_D Part-Hours ($x10^6$)	F_D Failures	λ_D Failure Rate (Per Billion Hours)
Resistors	5330.0	0	<0.19
Carbon Composition	1220.0	0	<0.82
Vitreous Enamel	210.0	0	<4.76
Wirewound	4000.0	0	<0.25
Capacitors	6320.0	0	<0.16
Mica	3600.0	0	<0.28
Paper	1880.0	0	<0.53
Polystyrene	840.0	0	<1.20
Inductors	4350.0	0	<0.20
Transformers	550.0	0	<1.82
Total	16550.0	0	<0.06

3.4 Microelectronics

Because of the current interest in microelectronics by both industry and government, a detailed discussion of the data collected on this part class is included.

Nearly 11 billion part-hours of data accumulated from field experience have been collected from user sources. Failure rates were calculated for most part classes. This data is presented in Table 3.4-I.

Table 3.4-II presents the user failure rates for digital and linear integrated circuits normalized in each case to the observed value for Class A screened parts. For digital devices, moving from screening Class B to A or from C to B halves the average failure rate. For linear devices moving from screening Class B to A quarters the average failure rate. No factor was calculated for linear Class C since data were not available. It should be noted that these factors are not intended to apply to specific microelectronic devices, but to indicate the average trend in reliability improvement which could be achieved by tightening screening procedures.

3.5 Factors

3.5.1 Storage Versus Dormancy

Preliminary examination of storage and dormancy data led to the tentative conclusion that part failure rates were substantially the same for both environments. A subsequent statistical analysis of the data confirmed this conclusion.

TABLE 3.4-I

Dormant Integrated Circuit User Data Summary

Part Type	t_D Part-Hours ($x10^6$)	F_S Fail-ure	λ_D Failure Rate (Per Billion Hours)
Class A	5863.736	6	1.02
Digital	5328.202	5	0.94
Linear	535.534	1	1.87
Class B	3120.254	7	2.24
General Class	615.000	0	<1.63
Digital	2269.720	5	2.20
Linear	235.534	2	8.49
Class C, Digital	1952.900	8	4.10
Total	10936.890	21	1.92

NOTE: Class A and Class B parts are high reliability.
Class C parts are Military Standard.

TABLE 3.4-II

Failure Rate Factors for Digital and Linear Integrated Circuits by Classes A, B, and C of MIL-STD-883

Integrated Circuit Type	Reliability Class	t_D Part-Hours	Failure Rate Factors
Digital			
	Class A	5328.202	1.0*
	Class B	2269.720	2.3*
	Class C	1952.900	4.4*
Linear			
	Class A	535.534	1.0**
	Class B	235.534	4.5**
	Class C	0	---

* Normalized to Class A, Digital

** Normalized to Class A, Linear

Brownlee's test (refer to Appendix A and Reference 15) for the comparison of two Poisson distributed observations was used to determine if a significant difference existed between the storage and dormancy failure rates.

The initial intent was to perform this test for each individual part type. This approach could not be used because so many part types exhibited no failures for one or both environments (Brownlee's test requires at least one failure from each population). Sufficient data to perform these tests were available for seven part classifications. These are listed in Table 3.5.1-I with their dormant and storage failure rates, F-statistic calculated using Brownlee's test, degrees of freedom for the F-statistic, and the rejection value. The null hypothesis of equal failure rates for the dormant and storage modes cannot be rejected for any of these classifications at the 5 percent significance level.

Failing to reject the hypothesis of equality is not the same as accepting it. A real difference could exist between the two populations, yet its magnitude might be so small that more data is needed to reveal it. In this case, any real difference is judged to be so slight that it can safely be concluded that no significant difference exists. For this reason dormancy and storage data have been combined for all analyses in this report.

3.5.2 Environmental

Because environment has a pronounced effect upon operating failure rates, an attempt has been made to determine the extent to which dormant failure rates are affected by various environmental conditions.

3.5.2.1 Temperature and Humidity

Excluding satellite data, greater than 85 percent of the data collected from equipment users have been accumulated in a controlled environment such that temperature and humidity were maintained relatively constant. Therefore, the average temperature range associated with these data is 75 ± 10°F. Likewise, the average humidity experienced by the equipments is estimated to be 60 ±15 percent. Because of the limited temperature and humidity ranges in most of the data, no pronounced differences in the dormant catastrophic failure rates can be identified. This is true for both Military Standard parts as well as high reliability parts.

TABLE 3.5.1-I

Brownlee's Test Results for Dormancy Versus Storage Data

PART TYPE	DORMANT FAILURE RATE λ_D (fits)	STORAGE FAILURE RATE λ_S (fits)	$\tilde{F}$ STATISTIC	$\tilde{F}$ STATISTIC DEGREES OF FREEDOM		$\tilde{F}_r$
				NUMERATOR	DENOMINATOR	
Capacitors						
Fixed, ER	0.35	1.38	1.99	4	22	3.44
Fixed, Non-ER	2.25	1.18	1.94	24	18	2.50
Connectors	1.65	5.10	1.79	4	2	39.25
Relays	29.90	27.10	1.05	42	18	2.38
Resistors, Fixed, Non-ER	0.65	0.49	1.04	24	10	3.37
Diodes, TX	0.46	0.38	1.03	12	6	5.37
Transistors, Silicon, Low Power	3.02	0.45	4.52	6	6	5.82

Reject the hypothesis of equal failure rate if $\tilde{F} \geq \tilde{F}_r$

$\tilde{F}_r$ is chosen to provide a significance level of 5 percent for a two-tailed distribution.

3.5.2.2 Location, Transportation, and Handling Factors

The collected data represent several different location environments which can be categorized for the purpose of deriving numerical location mode factors. Eleven major systems comprised of high reliability parts have been used to obtain the factors shown in Table 3.5.2-I. As depicted by the table, there are significant differences among the four location environments. To make the comparison, only the five primary part classes common to most systems were used: resistors, capacitors, diodes, transistors, and integrated circuits.

The location mode factors in Table 3.5.2-I have been normalized to the environment consisting of equipment in containers in a controlled environment. Almost without exception, the containers used are the type with internal environmental controls for temperature and humidity. In situations where the controls in the containers were not used, they were located inside an environmentally controlled facility. This environment is the closest to what might be termed a laboratory environment.

The satellite and submarine modes are self explanatory. The remaining mode consists of equipments which were not in a protective container, but were located in a facility with a controlled environment.

The location factors were calculated by combining the failure rates of all the electronic parts in each mode and determining the ratio of the total failure rate of each mode to the normalizing mode. Thus, the factor of the mode to which each other mode is normalized is unity. The location factors in Table 3.5.2-I include transportation and handling effects incidental to each mode. It should be noted that the factors given in this section are not intended as multipliers for the dormancy part failure rates shown in this report, but rather are intended as severity indicators.

The location mode factors shown in Table 3.5.2-I may be divided into their passive component (resistors and capacitors) and active component (transistors, diodes, and integrated circuits) constituents. Using the same data, Table 3.5.2-II has been developed showing these factors. As to be expected, the passive component factors are significantly less than those for the active components. The factors were obtained by the same methods used for Table 3.5.2-I.

TABLE 3.5.2-I

Normalized Dormancy Location Mode Factors for High Reliability Electronic Parts*

Dormant Environment	Location Mode Factor	(t_D) Part Hours of Experience ($\times 10^9$)
Satellite	0.3	25.95
Ground - Inside container in controlled environment	1.0	45.48
Ground - No container in controlled environment	3.3	4.22
Submarine	9.8	3.95

* Parts consist of resistors, capacitors, diodes, transistors, and IC's

TABLE 3.5.2-II

Normalized Dormancy Location Mode Factors for Passive and Active High Reliability Electronic Parts

Dormant Environment	Location Mode Factor	
	Passive Parts (Resistors and Capacitors)	Active Parts (Semiconductors and Microelectronics)
Satellite	0.2*	0.5
Ground - Inside container in controlled environment	1.0	1.0
Ground - No container in controlled environment	1.9	5.0
Submarine	7.4	13.1

* One failure was assumed to obtain this factor

3.6 Failure Rate Tables

3.6.1 Microelectronic Devices

The data in Table 3.6.1-I were available for the construction of Table 3.6.1-II, Catastrophic Dormant Failure Rates for Microelectronic Devices.

TABLE 3.6.1-I

Dormancy Data Available to Construct Microelectronic Device Failure Rate Chart

Microelectronic Device By Class A, B, or C	t_D Dormancy Experience Part-Hours $x10^6$	F_D Number of Failures	λ_D Failure Rate $x10^{-9}$ (fits)
Integrated Circuits			
Class A			
Digital	5328.202	5	0.94
Linear	535.534	1	1.87
Class B			
Digital	2269.720	5	2.20
Linear	235.534	2	8.49
Hybrid(Thin Film)	43.246	1	23.12
Class C			
Digital	1952.900	8	4.10

Table 3.6.1-II values of 1 and 2 fits chosen for Class A monolithic integrated circuits seem obvious. The Class B values of 2 and 7 fits are also fairly obvious - the rate of 8.49 fits being just closer to 7 than to 10. The value of 5 fits for Class C Digital was also chosen because 4.1 is closer to 5 than to 3 fits.

TABLE 3.6.1-II

Catastrophic Dormant Failure Rates (λ_D) for Microelectronic Devices

Catastrophic Dormant Failure Rates (Failures/Billion Part-Hours)	Military - Standard - 883		
	Class A	Class B	Class C
100.0			
70.0			Hybrid IC (Thin Film)
50.0			Hybrid IC (Thick Film)
30.0			
20.0		Hybrid IC (Thin Film)	Monolithic IC, Linear
15.0		Hybrid IC (Thick Film)	
10.0			
7.0		Monolithic IC, Linear	
5.0	Hybrid IC (Thin Film		Monolithic IC, Digital
3.0	Hybrid IC (Thick Film)		
2.0	Monolithic IC, Linear	Monolithic IC, Digital	
1.5			
1.0	Monolithic IC, Digital		

Class A – Devices intended for use where maintenance and replacement are extremely difficult or impossible, and reliability is imperative.

Class B – Devices intended for use where maintenance and replacement can be performed, but are difficult and expensive, and where reliability is imperative.

Class C – Devices intended for use where maintenance and replacement can be readily accomplished and down time is not a critical factor.

The value of 20 fits chosen for Class C linear integrated circuits (IC's) was based on rank ordering. By observing Class A, a ratio can be seen of two to one worse failure rate for linear compared with digital IC's and three and a half to one for Class B; a ratio of four fits to one would, therefore, not be unexpected for Class C.

It should be noted that there is only one data point for hybrid IC's - that for Class B (thin film) set at 20 fits in the table. Rank ordering (See Section 7.0, Glossary) has been used for placing the other hybrids in the table, also realizing the number of failure mechanisms listed for monolithic IC's is about 45. The number of failure mechanisms listed for hybrid (thick film) includes the 45 for monolithic IC's plus about 33 more or 78 total. The known mechanisms for hybrid (thin film) total twenty-nine more of which the most significant are electrolytic corrosion, migration, etc. The thin film hybrid is, therefore, regarded as somewhat more prone to failure than the thick film hybrid and the latter is set at 15 fits.

In Class A the ratio of hybrid (thick film) to the monolithic digital has been set at 3 to 1 rather than 7.5 to 1 as found in Class B. These factors tend to narrow down in the better grades and widen with the less reliable grades, which is why the hybrid (thick film) in Class C is set at 50. The hybrid IC's (thin film) are set at the next level higher than the thick film in all three classes in keeping with the judgment that they are somewhat less reliable than thick film because they are subject to a greater number of and more active type failure mechanisms.

3.6.2 Resistors and Capacitors

A catastrophic dormant failure rate table has been constructed for resistors and capacitors of Military Standard and high reliability grade (or class) of parts. Table 3.6.2-I is this table.

3.6.2.1 Resistors

The carbon composition resistor is a basic type useful for constructing a failure rate table. The accumulated Military Standard experience data amount to over 4.6 billion part-hours with no failures. This yields a failure rate of less than 0.21 fit. However, earlier data indicate a rate of 0.1 fit, and this value has been allowed to stand. Now if all the Military Standard grade data are added to the Established Reliability data, i.e., 22.3 billion part-hours with only one reported failure, the failure rate is about 0.05 fit. However, the Established Reliability failure rate has been placed at 0.07 fit as a conservative step.

TABLE 3.6.2-I

Catastrophic Dormant Failure Rates (λ_D) for Resistors and Capacitors

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Resistors		Capacitors	
	Military Standard (MIL-STD)	High Reliability (ER or Equivalent)	Military Standard (MIL-STD)	High Reliability (ER or Equivalent)
1000				
500				
200	Heaters			
100		Heaters	Tantalum, wet, slug	
70				
50	Variable carbon comp Variable wirewound Variable metal film		Aluminum Electrolytic	
30	Thermistors Varistors			
20			Variable ceramic (CV) Variable ceramic, tubular	Aluminum Electrolytic
15		Variable carbon comp Variable wirewound Variable metal film		
10		Thermistors Varistors	Variable air Variable trimmer, glass	Tantalum, wet, slug Variable ceramic (CV) Variable ceramic, tubular
7				
5	Carbon film		Tantalum, wet, foil	Variable air Variable trimmer, glass
3		Carbon film	Metalized mylar Metalized polycarbonate Metalized paper Foil, paper Foil, paper-mylar Mica	Tantalum, wet, foil

TABLE 3.6.2-I (Cont)

Catastrophic Dormant Failure Rates (failures/billion part-hours)

	Resistors		Capacitors	
	Military Standard (MIL-STD)	High Reliability (ER or Equivalent)	Military Standard (MIL-STD)	High Reliability (ER or Equivalent)
2	Wirewound, precision			Mica
1.5			Ceramic, general purpose	Metalized mylar Metalized polycarbonate Metalized paper Foil, paper Foil, paper-mylar
1	Wirewound, power	Wirewound, precision	Tantalum, solid Foil, mylar Foil, Polycarbonate Foil, Polystyrene	
0.7				Ceramic, general purpose
0.5		Wirewound, power		Tantalum, solid Foil, mylar Foil, polycarbonate Foil, polystyrene
0.3				
0.2	Metal film Tin oxide		Foil, teflon Ceramic, temperature compensating Procelain Glass	
0.15		Tin oxide		
0.1	Carbon composition	Metal film		Foil, teflon Ceramic, temperature compensating Porcelain Glass
0.0[illegible]		Carbon composition		
0.05				
0.02				
0.01				

The Military Standard metal film resistor data yield a failure rate less than 0.3 fit. This validates the failure rate determined earlier at 0.2 fit so it has been left standing. The tin oxide resistor is deemed equal to the metal film resistor in the Military Standard grade.

Data accumulated for the Established Reliability grade metal film resistor amount to about 12.5 billion part-hours with just one failure thus yielding a failure rate equal to 0.08 fit. This has been set at 0.1 fit. More recent data for the Established Reliability tin oxide resistor indicate a failure rate less than 0.21 so this has been placed at 0.15 - not quite as good as the metal film type in this grade.

The more recent Military Standard precision wirewound resistor data yield a failure rate less than 3 fits. This has been set at 2 fits, considerably better than the previous 5 fits. Wirewound power resistors are generally regarded as more reliable than the precision type so the failure rate has been set at 1 fit despite the data which indicates about 5 fits. This is a clear case of rank ordering and will be seen justified in the Established Reliability grade.

The recent Established Reliability wirewound resistor data for precision and power types are of the right order yielding failure rates of less than 1.27 and less than 0.47 fit respectively. These have been set at 1 and 0.5 fit respectively.

The more recent data for Military Standard carbon film resistors are not as plentiful as the earlier data. When the two sets of data are combined, the resulting failure rate remains about 5 fits where it stands. The Established Reliability grade of this resistor has a failure rate set at 3 fits by rank ordering, and is consistent with the more recent data yielding a failure rate of less than 9 fits.

The more recent data for Military Standard thermistors are considered better than previous data so the resulting failure rate of about 30 fits has been placed on the table along with varistors. The Established Reliability grade has been set at 10 fits by rank ordering because of too little available data.

In evaluating the data for variable resistors, it was not possible to segregate the data by type since then too little data would be available for each separate type; so data for all types were combined as being Established Reliability grade yielding a failure rate set at 15 fits. The Military Standard grade failure rate is set at 50 fits by rank ordering, there being insufficient data to do otherwise.

3.6.2.2 Capacitors

Both previous and recent data for Military Standard grade ceramic capacitors were combined for a failure rate of about 1.7 fits based on over 1.75 billion part-hours experience with 3 failures. This type was placed at 1.5 fits. The Established Reliability grade failure rate has been place at 0.7 fit based on 3.1 billion part-hours data with 2 failures yielding 0.64 fit. This also satisfies rank ordering.

The Established Reliability grade of solid tantalum capacitors has been set at a failure rate of 0.5 fit based on over 2 billion part-hours data with one failure. The Military Standard grade was set at 1 fit based on rank ordering, no recent data being available.

In the earlier report no distinction was made between wet foil and wet slug capacitors. When recent and previous data for the Military Standard grade capacitors are combined, the foil type appears inherently more reliable than the wet slug type. The Military Standard grade foil data yields a failure rate of just over 4 fits and has been set at 5 fits while the wet slug type is set at 100 fits based on 6 failures in 60.460 million part-hours. The Established Reliability grade wet foil capacitor is based on data yielding a failure rate of less than 6.9 fits and rank ordering. The Established Reliability wet slug failure rate is set at 10 fits based on data yielding a failure rate of 9.3 fits. It will be seen that the data now clearly support a distinction between wet foil and wet slug in both Military Standard and Established Reliability grades.

The failure rate for the Established Reliability aluminum electrolytic capacitors was set at 20 fits based on data yielding a failure rate of less than 164 fits and other capacitor experience. The Military Standard grade failure rate was set at 50 fits.

The failure rate for the Military Standard grade mica capacitor was set at 3 fits based on data yielding a failure rate less than 3.4 fits. When the recent data are combined with the previous data, the failure rate is still less than 4 fits. The failure rate for the Established Reliability grade has been set at 2 fits based on rank ordering even though the data yield a failure rate of 2.8 fits.

In setting a failure rate for the Established Reliability glass capacitor, all the recent data were added to the previous and recent Military Standard grade data for a total of over 1 billion part-hours with no failure; then the failure rate was set at 0.1 fit. This can be justified as a conservative step since the Military Standard quality is regarded as less than that of the Established Reliability grade. The Military Standard grade failure rate of 0.2 fit was set by rank ordering.

The Military Standard grade metalized paper capacitor failure rate was left at 3 fits where it was set previously, rather than show a worse failure rate of 6 fits as indicated by a somewhat limited amount of data. The Established Reliability grade was set at 1.5 fits by rank ordering. All other metalized dielectric capacitors were set at least equal to the metalized paper dielectric capacitor type by rank ordering.

The Military Standard variable trimmer piston (glass) capacitor failure rate was set at 10 fits based on data yielding a failure rate of less than 11.8 fits. Other variable capacitor types in both Military Standard and Established Reliability grades have failure rates set by rank ordering.

Any other capacitor types in both Military Standard and Established Reliability grades not having substantial data have failure rates based on rank ordering.

3.6.3 Semiconductors: Transistors and Diodes

A catastrophic dormant failure rate table (Table 3.6.3-I) has been constructed for semiconductors of Military Standard and high reliability grade.

3.6.3.1 Diodes

The high reliability and tested extra (TX) category of semiconductor data appears to be adequate for constructing a failure rate table because it comprises a larger quantity of data on a larger variety of semiconductors. The Military Standard grade of semiconductors has been arranged in the table mostly by rank ordering using the small amount of available data where possible.

The high reliability and TX grade of diodes has a failure rate set at 0.3 based on over 7.6 billion part-hours and 3 failures yielding 0.39 fit. The Military Standard grade has been allowed to stand at 0.7 fit based on previous data and satisfied rank ordering.

TABLE 3.6.3-I

Catastrophic Failure Rates (λ_D) for Semiconductors*

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Transistors*		Diodes*		
	Military Standard (MIL-STD)	High Reliability and TX	Military Standard (MIL-STD)	High Reliability and TX	
1000					1000
500					
200					
100					100
70					
50	Unijunction		Microwave diode		
30			Silicon controlled rectifier, SCR; Microdiode		
20	Field effect, (FET)	Unijunction			
15				Microwave diode	
10		Field effect, (FET)	Tunnel diode	Microdiode; Silicon controlled rectifier (SCR)	10.0
7			Varactor		
5	PNP			Tunnel diode	
3	NPN		Bridge, 4 diodes encapsulated	Varactor	
2					
1.5		PNP	Zener	Bridge, 4 diodes encapsulated	
1		NPN		Zener	1.0
0.7			Signal diode		
0.5					
0.3				Signal diode	
0.1					0.1
0.05					
0.02					
0.01					0.01

*All devices are silicon, Si

The Military Standard grade microdiode failure rate has been left standing at 30 fits as before. The failure rate for the high reliability and TX grade was set by rank ordering.

Too little data have been found available for varactors, tunnel diodes, and microwave diodes; therefore, failure rates have been set by rank ordering as found in Table 3.6.3-I.

The failure rate for the high reliability and TX grade zener diode has been set at 1.0 fit based on the recent data of 898 million part-hours of high reliability and TX experience plus the (higher risk) Military Standard data of 607 million hours, which is a conservative step. The Military Standard grade failure rate has been set at 1.5 to satisfy the data failure rate of less than 1.65 fits and is also in accord with rank ordering.

Failure rates for the encapsulated four diode bridge rectifiers were set by rank ordering in both Military Standard and high reliability and TX grades.

The high reliability and TX grade silicon controlled rectifier (SCR) failure rate has been set at 10 fits in accordance with the recent data failure rate of less than 17.4 fits. The Military Standard grade silicon controlled rectifier failure rate has been set at 30 fits by rank ordering. The SCR's have been included with diodes rather than transistors for consistency with other government publications.

3.6.3.2 Transistors

The failure rate of the NPN silicon transistor in the high reliability and TX grade has been set at 1 fit based on over 3 billion hours experience and 4 failures. Similarly the PNP failure rate has been set at 1.5 fits based on the recent data failure rate of 1.46 fits. The Military Standard failure rate for the NPN silicon transistors has been set at 3 fits based on the recent data failure rate of less than 4.4 fits. Three fits is also the same rate established previously. The failure rate for the PNP Military Standard grade low power transistor has been set by rank ordering.

The high reliability and TX grade of field effect transistor has a failure rate set at 10 fits based on the recent data rate of less than 14 fits. The Military Standard grade failure rate was set at 20 fits based on rank ordering.

The high reliability and TX grade of unijunction transistor failure rate was set at 20 fits based on rank ordering, and the Military Standard grade failure rate was set at 50 fits based on rank ordering. There is very little recent data available.

In summary, the same may be said for the transistor failure rate table as has been said for the diode table. That is, the lowest basic failure rates are those best supported by data. Rank ordering has only been used where gaps in the collected data have appeared.

3.6.4 Low Population Parts

A catastrophic dormant failure rate table (Table 3.6.4-I) has been constructed for low population parts of Military Standard and high reliability grade.

3.6.4.1 Transformers and Other Inductive Devices

To determine a failure rate for RF chokes and coils, all the previous and recent data were added to yield 414 million part-hours with zero failures and failure rate less than 2.4 fits. The failure rate has thus been set at 3 fits for high reliability and 5 fits for the Military Standard grade. This represents a considerable improvement over rates set formerly. In addition, there are the high reliability grade data for RF transformers yielding a failure rate of less than 4.8 fits based on 208 million hours and zero failures. This further confirms the set failure rates.

The best data for the audio transformer come from the high reliability source and yield a failure rate of 3.2 fits based on 633 million part-hours experience with 2 failures. On this basis a failure rate of 3 fits has been set for the high reliability grade and 5 fits for the Military Standard grade by rank ordering.

Power transformer data from high reliability sources yield a failure rate of less than 12 fits based on 83 million part-hours with no observed failures. The Military Standard source data amount to 509 million part-hours with 9 failures and a failure rate of 17.7 fits for transformers. The failure rates have thus been set at 10 fits for high reliability and 20 fits for Military Standard grades based on data and rank ordering.

Pulse transformer data from high reliability sources have been combined with previous data to yield 42.6 million part-hours with no failures yielding a failure rate of less than 21.6 fits. A failure rate of 10 fits has thus been set for high reliabiltiy grade and 20 fits for the Military Standard grade.

Inductor and reactor data from high reliability sources total 280.4 million part-hours with no failures and failure rate less than 3.5 fits. A failure rate of 2 fits has been set for the high reliability grade and 3 fits for the Military Standard grade. These rates are comparable with those previously established.

Magnetic memory core data from high reliability sources amount to 24.77 billion part-hours experience with no failures yielding a failure rate less than 0.04 fits. The failure rate set for this is 0.02 fit for the high reliability grade and 0.03 for the Military Standard grade based on rank ordering.

TABLE 3.6.4-I

Catastrophic Dormant Failure Rates (λ_D) for Low Population Devices

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Military Standard (MIL-STD)	High Reliability	Military Standard (MIL-STD)	High Reliability	
1000.0	DC Torquers				1000
500.0	AC motor tachometer Gyros	DC torquers	Stepping switch, telephone		
200.0	AC servos	AC motor tachometer Gyros	Circuit breaker Inertial switch, contactor Thermostat, thermal switch Humidity control switch Incandescent lamp	Stepping switch, telephone	
100.0	Accelerometer	AC servos	Microswitch Pressure switch Primary battery, silver zinc	ircuit breaker nertial switch, contactor Thermostat, thermal switch Humidity control switch Incandescent lamp	100
70.0		Accelerometer	Luminescent lamp		
50.0	DC power, motors DC power, generators		Toggle switch Quartz crystal, Frequency	Microswitch Pressure switch Primary battery, silver zinc	
30.0		DC power, motors DC power, generators	Relay	Toggle switch Quartz crystal, frequency Luminescent lamp	
20.0	AC power, induction motor AC power, synchronous motor AC power, generators Power transformer		Solar cell		
15.0				Relay	
10.0		AC power, induction motor AC power, synchronous motor AC power, generators Power transformer		Solar cell	10.0
7.0					
[illegible]	RF transformers RF chokes and coils Audio transformer				
3.0	Inductors, reactors	RF transformers RF chokes and coils Audio transformer	Connectors		
2.0		Inductors, reactors		Connectors	
1.5					

TABLE 3.6.4-1 (Cont)

Catastrophic Dormant Failure Rates (failures/billion part-hours)	Military Standard (MIL-STD)	High Reliability	Military Standard (MIL-STD)	High Reliability	
1.0					1.0
0.7					
0.5					
0.3					
0.2					
0.15					
0.1					0.1
0.05					
0.03	Magnetic memory core		Solder connection		
0.02		Magnetic memory core	Connector pin, male or socket		
0.01				Solder connection	
0.01				Connector pin, male or socket	0.01

3.6.4.2 Relays and Switches

High reliability relay data yield a failure rate of 17.6 fits from 568 million part-hours experience and 10 failures. Military Standard grade data amount to 472 million part-hours with 18 failures and failure rate of 38 fits. Failure rates of 15 and 30 fits respectively have been set for both grades.

High reliability data for stepping switches amount to 5 million part-hours with 2 failures and failure rate of 400 fits. A failure rate of 200 fits has bee, set for the high reliability grade and 500 fits for the Military Standard grade, which is better than previous rates. A telephone type stepping switch is assumed.

Total data from recent and previous experience for toggle switches amount to about 10 million part-hours and no failures with failure rate less than 100 fits. Thus the Military Standard grade failure rate could be left at 100 fits and the high reliability grade at 50 fits as before. However, the general class of high reliability switch data indicates a failure rate of less than 31 fits with 32 million part-hours experience and no failures. For this latter reason, the failure rates have been set at 30 fits for the high reliability grade and 50 fits for Military Standard grade.

Microswitch and pressure switch failure rates have been set at 50 fits for high reliability and 100 fits for Military Standard grade by rank ordering. Too little experience data were available for decision making.

Thermostat, thermal switch, and humidity control switch failure rates have been set at 100 fits for high reliability and 200 fits for Military Standard grades by rank ordering, with too little data available for other bases for decision making. These rates are somewhat better than those set previously.

The inertial switch, contactor, and circuit breaker failure rates have also been left at 200 fits for the Military Standard grade and 100 fits for the high reliability grade as before. Lack of available data precludes any change at this time.

3.6.4.3 Solar Cells

A failure rate of 10 fits has been set for solar cells of high reliability grade based on 748 million part-hours data with 8 failures and failure rate of 10.7 fits. The failure rate for the Military Standard grade has been set at 20 fits based on rank ordering.

3.6.4.4 Quartz Crystals

A failure rate of 30 fits has been set for frequency determining quartz crystals of high reliability grade based on 20 million part-hours experience with no failures and failure rate of less than 50 fits. The Military Standard grade failure rate is set at 50 fits by rank ordering. These rates represent an improvement factor of about two times.

3.6.4.5 Lamps

High reliability data for incandescent lamps amount to 9.5 million part-hours with 1 failure and failure rate of 105 fits. The failure rate has thus been set at 100 fits for this grade and 200 fits for Military Standard grade.

High reliability data for electroluminescent lamps amount to 27.3 million part-hours with one failure and failure rate of 37 fits. The failure rate has so been set at 30 fits for high reliability and 70 fits for the Military Standard grade.

3.6.4.6 Primary Batteries, Silver Zinc

The high reliability data for these batteries are too small to develop a failure rate with any validity. It only indicates a failure rate less than 5000 fits. A failure rate of 100 fits for Military Standard grade and 50 fits for high reliability is, therefore, set based on other information.

3.6.4.7 Rotating Devices

Too little data are available to warrant any change in failure rates from those previously set for motors, generators, or electric motor driven devices. The previous rates have been retained for this entire category. The same holds true for gyros.

3.6.3.8 Connectors and Connections

Connector data from high reliability sources amount to 800 million part-hours with 1 failure and failure rate of 1.25 fits. The failure rate has thus been conservatively set at 2 fits for this grade and 3 fits for Military Standard grade. These rates include an indeterminate number of pins per connector.

A large quantity of 55.4 billion pin-hours has been collected from high reliability sources for connector pins with no failures and resulting failure rate of less than 0.02 fit. A failure rate of 0.01 has thus been set for high reliability grade pins and 0.02 fit for Military Standard grade. These "pins" include socket (receptacle) pins or male pins.

Soldered connections data from high reliability sources include 34.9 billion joint-hours with no failures and failure rate of less than 0.03 fit. Based on this a failure rate for high reliability has been set at 0.015 fit while 0.03 fit has been set for the Military Standard grade.

3.7 Average Failure Rates, Relationships, Ratios, and Enhancement Factors

3.7.1 Electronic Systems

The system data collected have been grouped and analyzed to determine average dormant failure rates and factors and to evaluate the reliability growth of electronic systems.

3.7.1.1 Average Dormant Part Failure Rates for Various Systems

Fifteen systems were used to determine the average dormant part failure rates for the different part classes shown in Table 3.7.1.1-I. The systems are coded by alphabetical letters and ranked in order of increasing failure rate within each part class. In the table, the category, Basic Electronic Parts, consists of capacitors, resistors, diodes, transistors, and integrated circuits. The other category, Electronic and Electromechanical Parts, includes the basic electronics plus such parts as relays, inductive devices, transformers, and switches. The average catastrophic failure rate for each part class is denoted by $\bar{x}$ in the "System" column.

As evidenced by Table 3.7.1.1-I, there is a wide variation in average electronic part failure rates for the various high reliability systems. This is due to a number of factors such as the part mix involved; the actual high reliability grade used; e.g., established reliability grades for passive devices may be l, m, p, r, s or IC's may be class A or B; the vintage of the design and parts used, which varies by several years; and the failure reporting methods used by the different sources. Therefore, it is not practical to attempt a further breakdown of the high reliability categories.

3.7.1.2 Dormant Part Class Factors

The data contained in Table 3.7.1.1-I may be used to obtain factors depicting the relative differences between the average failure rates in each part class. These factors are shown in Table 3.7.1.2-I, which has been developed by normalizing the average part class failure rates to the basic electronic, high reliability failure rate. ~~The~~ table shows that the average dormant electronic failure rate for military standard parts is approximately 4 times as high as that for high reliability parts. The dormant failure rate for ultimate class parts appears to be 7 to 10 times better than that for high reliability; however, there are not sufficient data in the ultimate class to make good comparisons.

TABLE 3.7.1.1-I

Average Catastrophic Dormant Part Failure Rate (λ_D) by Part Quality Level for Various Systems

Part Class or Quality Level	Basic Electronic Parts: System	Basic Electronic Parts: Average Catastrophic Part Failure Rate (λ_D) In Dormancy (Fits)	Basic Electronic Parts: t_D Part-Hours Experience (10^9)	Electronic and Electromechanical Parts: System	Electronic and Electromechanical Parts: Average Catastrophic Part Failure Rate (λ_D) In Dormancy (Fits)	Electronic and Electromechanical Parts: t_D Part-Hours Experience (10^9)
1. Commercial	*		*	*		*
2. Military Standard	a	2.1	38.628	a	2.6	40.665
	b	4.1	1.953	b	4.1	1.953
	$\bar{x}$	2.2	40.581	$\bar{x}$	2.7	42.618
3. High Reliability	c	<0.1**	9.890	c	<0.1**	10.634
	d	0.2	15.969	d	0.2	16.028
	e	0.3	13.366	f	0.3	2.937
	f	0.4	2.680	g	0.5	15.623
	g	0.4	14.978	h	0.5	9.732
	h	0.5	9.345	e	1.0	14.348
	i	0.8	3.850	j	1.1	1.757
	j	1.2	1.615	k	1.3	1.532
	k	1.9	0.514	i	1.7	4.155
	l	2.1	2.344	m	2.1	2.877
	m	2.3	2.608	n	2.3	5.195
	n	2.3	5.184	l	2.5	2.404
	$\bar{x}$	0.6	82.343	$\bar{x}$	0.8	87.222
4. Ultimate	o	<0.086**	11.650	o	<0.06**	16.550

* No Data
** One Failure Assumed

TABLE 3.7.1.2-I

Average System Factors For Dormancy by Part Classes

Part Class or Quality Level	Basic Electronics Part Factor	Electronics & Electromechanical Part Factor
Commercial	*	*
Military Standard	3.7	4.5
High Reliability	1**	1.3
Ultimate ***	<0.14***	<0.10***

* No Data

** All Other Factors Normalized to this Part Class and Type

*** One Failure Assumed

3.7.1.3 Reliability Growth for Dormant Electronic Systems Utilizing High Reliability Parts

Five systems with similar functions and containing high reliability parts have been used to determine reliability growth for dormant systems. Figures 3.7.1.3-1 and 3.7.1.3-2 show the system catastrophic dormancy failure rates versus the average vintage of the design and parts used in the systems.

A curvilinear regression analysis has been performed to determine failure rate trends. The curves obtained as a result of the regression analyses are on the respective Figures 3.7.1.3-1 and 3.7.1.3-2. Values calculated and the equations derived during the regression analyses are shown in Tables 3.7.1.3-I and 3.7.1.3-II. The curve for Figure 3.7.1.3-2 has the best fit to the data since its coefficient of determination is 94.3% as compared to 84.1% for the curve for Figure 3.7.1.3-1. The closer this coefficient is to 100%, the better the fit; 100% is a perfect fit.

Based upon the data trends indicated by the two curves, there has been a steady improvement in catastrophic dormancy failure rates from 1964 to 1969. However, the rate of improvement has leveled off somewhat after 1967 and appears to be asymptotically approaching a level failure rate line at a much slower rate after 1969.

The question of the cause of these apparent improvement trends in high reliability parts arises. The answer is a combination of standardizing to as few types of components as possible, of developing and enforcing stringent parts specifications, of captive (or dedicated) manufacturing lines under strict process control, and of much more stringent screens and longer burn-in hours. Paragraph 3.7.1.4 discusses in depth the effects of screening and burn-in.

3.7.1.4 Screening and Burn-In Enhancement Factors

The question is often asked: "Why spend the money to burn-in another 100 hours, e.g., from 168 hours to 268 hours, when you can scarcely cut the dormant failure rate in half?" The answer is that while it is true that the dormant failure rate is only about halved (thus doubling the trouble free time in dormancy) it is also true that the ground operating failure rate is cut by at least four or five times (thus increasing the trouble free time of operation on the ground by the same factor of four or five times). Table 3.7.1.4-I shows this to be true because of the change in enhancement factors for different reliability grade parts.

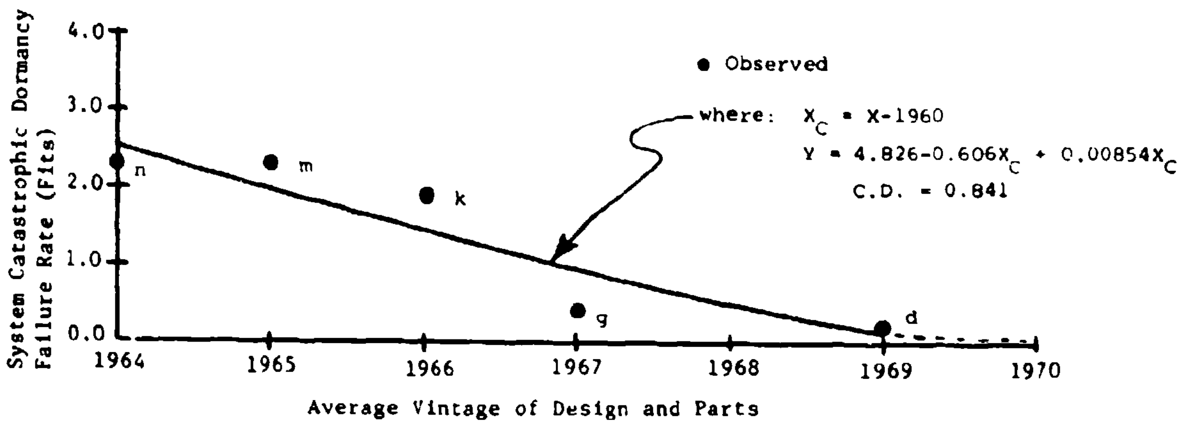


Figure 3.7.1.3-1 Reliability Growth for High Reliability Electronic Parts in Dormant Electronic Systems

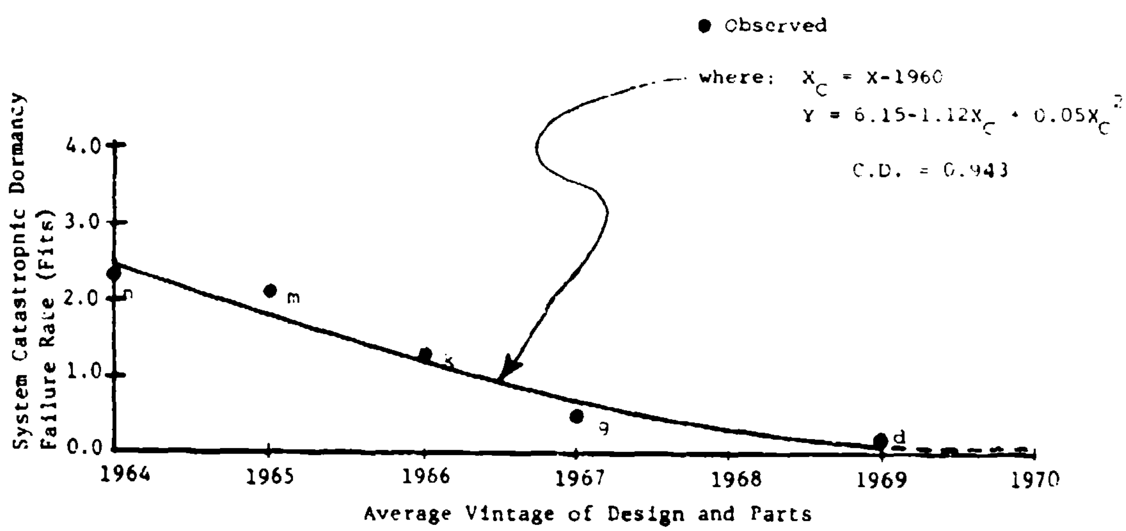


Figure 3.7.1.3-2 Reliability Growth for High Reliability Electronic and Electromechanical Parts and Components in Dormant Electronic Systems

TABLE 3.7.1.3-I

Parameters Calculated for Regression Analysis
(Shown in Figure 3.7.1.3-1)

Actual Observed Values x(YR.)	Actual Observed Values y(Fits)	Coded Values of x $x_c = x - 1960$ (Years)	Calculated Values of y (Fits)
1964	2.3	4	2.54
1965	2.3	5	2.01
1966	1.9	6	1.50
1967	0.4	7	1.00
1969	0.2	9	0.06

Fitted Equation: $y = 4.826 - 0.606x_c + 0.00854x_c^2$

Coefficient of Determination: 84.1%

TABLE 3.7.1.3-II

Parameters Calculated for Regression Analysis
(Shown in Figure 3.7.1.3-2)

Actual Observed Values x(YR.)	Actual Observed Values y(Fits)	Coded Values of x $x_c = x - 1960$ (Years)	Calculated Values of y (Fits)
1964	2.3	4	2.47
1965	2.1	5	1.80
1966	1.3	6	1.23
1967	0.5	7	0.76
1969	0.2	9	0.13

Fitted Equation: $y = 6.15 - 1.12x_c + 0.05x_c^2$

Coefficient of Determination: 94.3%

The data in Table 3.7.1.4-I tend to display a linear relationship on the log - log plot shown on Figure 3.7.1.4-1. The usefulness of this curve is readily apparent because it directly relates burn-in time (and cost) to those dormancy failure rates that are realistically achievable for state-of-the-art devices under current manufacturing processes, controls, and tests.

The plot of Figure 3.7.1.4-1 takes the asymptotic form for the linear portion, as

$$y = ax^{-n} \qquad \text{(Equation 3.7.1.4-1)}$$

where:
- y = y axis value (average part failure rate)
- x = x axis value (burn-in hours)
- a = coefficient (to be derived empirically)
- n = negative exponent (to be derived empirically).

For the linear portion of Figure 3.7.1.4-1 the general form, Equation 3.7.1.4-1 becomes:

$$y = \frac{1.72\, x^{-1.235}}{10^{6}} \qquad \text{(Equation 3.7.1.4-2)}$$

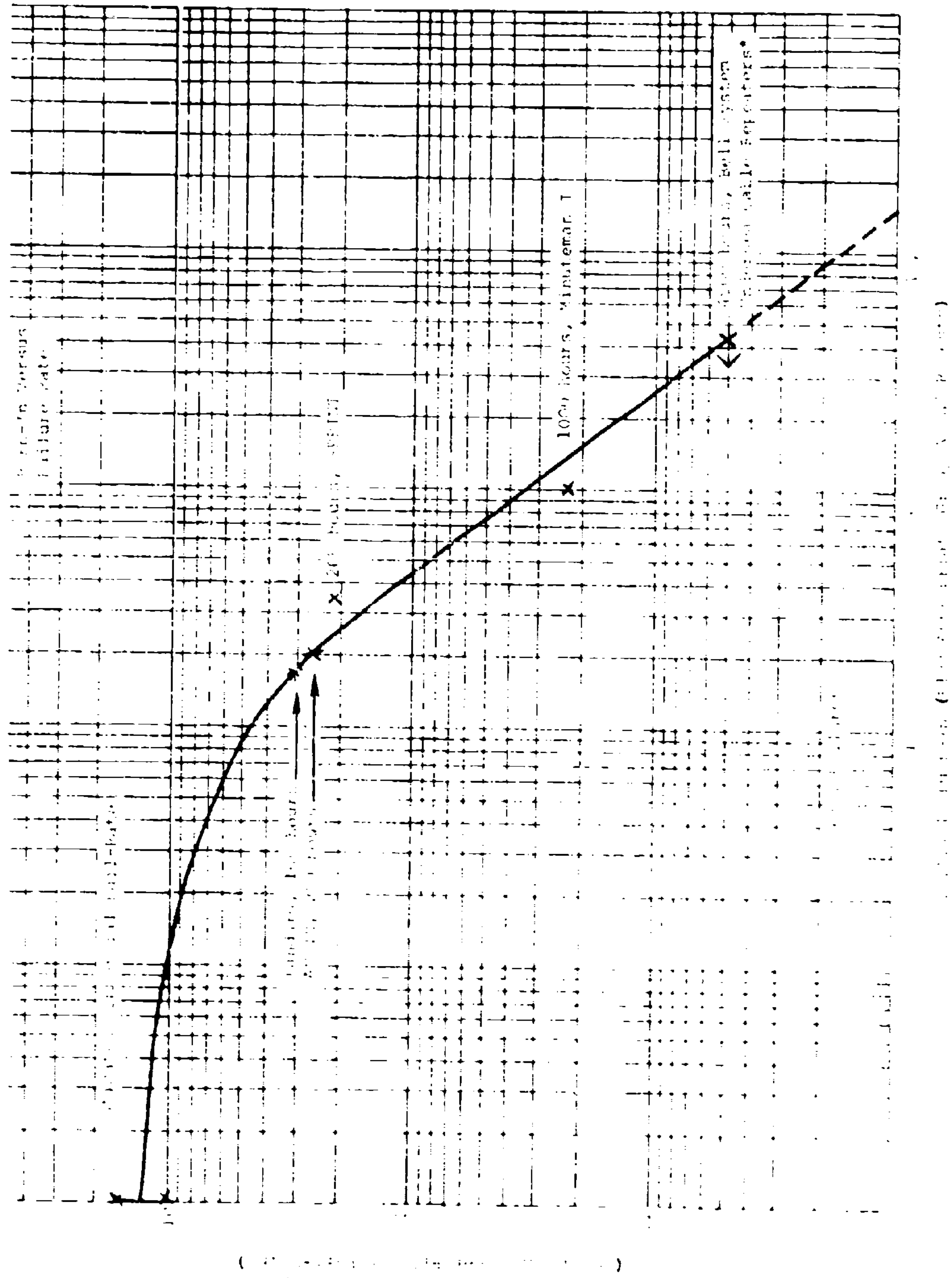
TABLE 3.7.1.4-I

$K_{E/D}$ Ratios for Various Part Classes
(Based on Average Part Failure Rates)

Part Class or Quality Level	Ground Operating Failure Rate ($\times10^{-9}$) λ_E (Note 1)	Ratio $K_{E/D}$	Failure Rate ($\times10^{-9}$) λ_D	t_B Burn-In Hours
Commercial (Estimated)	500-700	50-70X	10-15	
Military Standard	166	35X	4.7	
Standard Burn-In	80	25X	3.08	168
JANTX	40	15X	2.6	200
SPRINT (High Reliability)	15	7.5X	2.3	268
Minuteman I (High Reliability)	1.5	6X	0.25	1000
Also an estimate of the failure rates that are the "ultimate" for today's technology can be derived from Bell System undersea cable repeater parts as follows:				
Transistors	<5	3X	<2.0	4500
Diodes	<1	3X	<0.3	4500
Resistors and Capacitors	<0.1	3X	<0.03	4500
Overall Electronic	<0.15	3X	<0.06	4500

Estimated Value (no observed failures)

Note 1: Ground operating covers a wide range of environments from relatively benign to ground mobile.


1000 Hours, Minuteman I

3.8 Parameter Drift During Dormancy

While it is well known that catastrophic electronic part failures occur in dormancy, the problem of parameter drift with age is of equal importance. Yet, very little quantitative data exist in this area. Available information is summarized below.

3.8.1 USAF Electronic Equipment Age and Wearout Evaluation

In 1968, the U. S. Air Force conducted a study on a total of 1074 high reliability electronic parts which had been in dormant operational use for approximately 5 years. A statistical comparison of critical part parameters was made before and after the 5 years of field experience in a controlled environment. The total sample of parts, as shown in Table 3.8.1-I, had been subjected to high reliability burn-in and screening. The results showed that parameter drift was occurring but at a very slow rate. Conclusions, based on the assumption that drift was linear with time, indicated that the lifetime of the discrete parts being studied was greater than 10 years. End of life is defined as mean parameter drift outside of the specified tolerance band. Thus, it is possible for some parts to drift outside of specification limits while the group mean will be within tolerance. To have complete confidence that electronic part parameter drift will not present a problem after 10 years of dormancy, the extrapolated ±3 sigma values should be within the tolerance band.

3.8.2 Martin Marietta Parts Certification Program

In 1971, Martin Marietta completed the first phase of parameter drift tests on 7619 high reliability electronic parts which had been in laboratory storage for an average duration of 3.4 years. The total sample sizes for the various parts included in the study are shown in Table 3.8.2-I. The samples were representative of the various part types commonly used by the aerospace industry.

Parameter measurements were taken before, during, and after storage. Trend lines were calculated using linear regression analysis for both the group means and the ±3 sigma values. Observed drift of the semiconductors and capacitors was so small that the differences were within the accuracy of the test equipment. Wet tantalum and aluminum electrolytic capacitors were not included in the program. Positive drift was noted with both film and wirewound resistors. However, these devices were originally purchased with group means below the nominal value so a linear extrapolation of the observed drift indicates a lifetime of greater than 10 years. The ±3 sigma trend line for wirewound resistors passed outside the upper tolerance limit at approximately 9 years. The small sample sizes for relays and switches precluded meaningful statistical analysis of parameter drift. Less than 1 percent of the magnetic devices under test can be expected to drift out of specification limits after 5 years storage. Additional details can be found in Reference 3.

3.8.3 MARK 12 Aging and Surveillance Program

The U. S. Air Force is presently conducting a Mark 12 Aging and Surveillance Program in which representative samples of electronic assemblies are periodically removed from storage and tested to determine parameter drift. The collected data are then analyzed by a computer program which results in service life estimates for replaceable items. This program is significant because approximately 335 IC's are being subjected to aging. The first data on these microelectronic devices is expected to be available late in fiscal year 1974.

TABLE 3.8.1-I

1968 USAF Parameter Drift In Dormancy Study

High Reliability Part Category	Total Parts In Dormancy	t_D Total Dormancy Part-Hours Accumulated
Resistors	395	17,881,650
Diodes	294	13,309,380
Transistors	291	13,173,570
Capacitors	94	4,255,380
Total	1074	48,619,980

TABLE 3.8.2-I

Martin Marietta Storage Life Tests

High Reliability Part Category	Total Parts	t_S Total Part-Hours Accumulated
Magnetics	776	11,786,580
Capacitors	330	10,485,720
Resistors	4951	135,869,352
Semiconductors	1534	55,100,620
Relays and Switches	28	1,042,440
Total	7619	224,284,712

3.9 Failure Modes and Mechanisms

A list of 98 failures, whose modes and mechanisms have been identified as occurring during dormancy, is contained in Table 3.9-I. These failures occurred on parts which were assembled into complete systems so the environment is not shelf life but rather storage in a container or operational use under dormant conditions.

As a marked contrast to the effect observed with power on-off cycling (see Section 4.5), open and short failure modes are about equally divided in the dormancy table. Major causes of shorts are capacitor dielectric breakdown and wet electrolyte leakage together with conductive particle contamination in IC's. Surface passivation will prevent failures attributed to conductive particles. Although examples of "purple plague" are no longer seen, other types of intermetallic problems are still observed as evidenced by integrated circuit failures in the open mode from sources A and D.

Electrolysis of metal film resistance elements with entrapped humidity can create opens after a period of time in dormancy. Use of

TABLE 3.9-I

Systems Failure Occurring During Dormancy

System	Quantity	Part Type	Failure Mode	
A,D	4	Integrated Circuit	Open	Lifted B Pr
A	1	Integrated Circuit	Short	Corrosio
E	1	Integrated Circuit	Open	Bond Fai
F	29	Integrated Circuit	Short	Contamin
F	3	Integrated Circuit	Open	Cracked
F	1	Integrated Circuit	Short	Oxide De
A,B,F	10	Transistor	Open	Bond Lif
B,F,	3	Transistor	Short	Contamin
F	2	Transistor	Open	Corrosio
A	1	Capacitor, Tantalum	Drift	Excessiv
C,F	12	Capacitor, Ceramic	Short	Defectiv
F	2	Capacitor, Tantalum, Wet	Short	Electrol
A	2	Lamp	Open	Defectiv
A	1	Thermistor	Drift	Resistan
A	6	Accelerometer	Leakage	Seal Fai
F	9	Resistor, Metal Film	Open	Nichrome
F	4	Resistor, Metal Film	Open	Flaking
C,F	2	Resistor, Variable	Open	Defectiv
F	1	Resistor, Wirewound	Open	Nicked W
C,D,F	3	Diode	Open	Loose/Br
E	1	Filter, Feedthrough	Open	Crack In
	98	Total		

System Code

A = Space Vehicle
B = Interceptor
C = Ground Support
D = Satellite (Ground Test)
E = Surface To Air Missile
F = Surface To Surface Missile

TABLE 3.9-I

Systems Failure Occurring During Dormancy

Part Type	Failure Mode	Description
Integrated Circuit	Open	Lifted Ball Bond, Intermetallic Problem
Integrated Circuit	Short	Corrosion Over Metalization
Integrated Circuit	Open	Bond Failure, Cause Unknown
Integrated Circuit	Short	Contamination
Integrated Circuit	Open	Cracked Die
Integrated Circuit	Short	Oxide Defect
Transistor	Open	Bond Lifted From Die
Transistor	Short	Contamination
Transistor	Open	Corrosion
Capacitor, Tantalum	Drift	Excessive Electrical Leakage
Capacitor, Ceramic	Short	Defective Dielectric
Capacitor, Tantalum, Wet	Short	Electrolyte Leakage
Lamp	Open	Defective Termination
Thermistor	Drift	Resistance Change, Unknown Cause
Accelerometer	Leakage	Seal Failure
Resistor, Metal Film	Open	Nichrome Electrolysis
Resistor, Metal Film	Open	Flaking From Ceramic Core
Resistor, Variable	Open	Defective Weld
Resistor, Wirewound	Open	Nicked Wire in Manufacture
Diode	Open	Loose/Broken Chip
Filter, Feedthrough	Open	Crack In Ceramic Sleeve
Total		

round Test)
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thicker film elements will prevent this problem. Although not listed in the table, it is theoretically possible for electromigration to cause opens in integrated circuit aluminum metalization when subjected to low level power in a dormant application. Extensive research, resulting in quantification of this phenomenon, has been performed by Dr. John Venables of the Martin Marietta Corporate R & D Laboratories/Research Institute for Advanced Studies. Details of Dr. Venables' work are given in Reference 18. This problem is being solved by vendor control over grain size and the use of relatively thicker metalization.

4.0 POWER ON-OFF CYCLING EFFECTS

4.1 Introduction

The purpose and intent of the Power On-Off Cycling program has been the collection, study, and analysis of electronic equipment reliability data to determine power on-off cycling effects on reliability of military equipment. No testing of electronic items has been done to obtain data, but rather an extensive data survey and collection effort was undertaken to locate and obtain the necessary data.

The equipment studied was typical of those used to perform electronic functions in military ground, airborne, missile, missile shipboard, and satellite applications. Special emphasis was given to the area of microelectronics. In addition, some data on electrical, electromechanical, and nonelectronic devices applicable to electronic military systems were available and have been included, but no special effort was made for these categories.

4.1.1 Limitations of Study

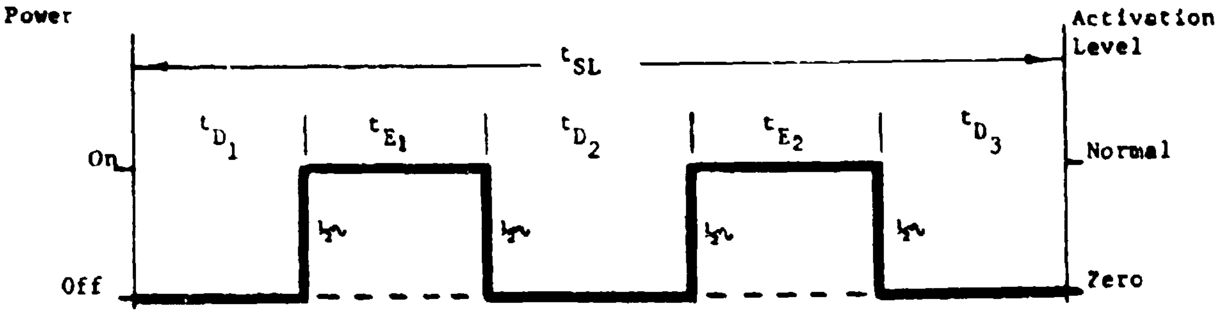
A power on-off cycle has been defined as that state during which an electronic system goes from the zero or near zero (dormant) electrical activation level to its normal system activation level (turn on) plus that state during which it returns to zero or near zero (turn off), or vice versa. Figure 4.1.1-1 illustrates some idealized typical power on-off cycles. The normal system activation level, for this study, has been defined as that electrical stress/energy which, under normal systems operation, is applied to each and every part or component which may or may not have been derated for reliability enhancement.

The scope of this study also has been

1 To include failures occurring during, or as a result of normal turn-on or shut down

2 To correlate failure incidence with power on-off cycling rates and energized state

3 To correlate failure incidence with application (ground, airborne, etc.) and with equipment type (radar, communication, etc.)



NOTE: Symbols are defined in Section 8 herein.

Figure 4.1.1-1. Typical Power On-Off Cycle (Idealized)

4 To correlate failure incidence with other electronic equipment characteristics (part types, part quality, thermal and electrical stress, cycling rates, and electrical transient suppression).

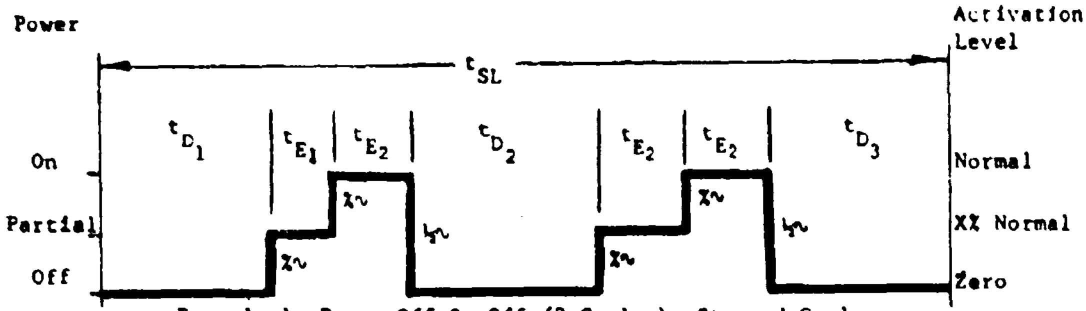
This study does not include power cycles which have varying levels of electrical power applied, nor does it include on-off power cycles which impose a lengthy time constraint for power turn on or turn off. Figure 4.1.1-2 depicts such power on-off cycles excluded from this study.

4.1.2 Need for Additional Data

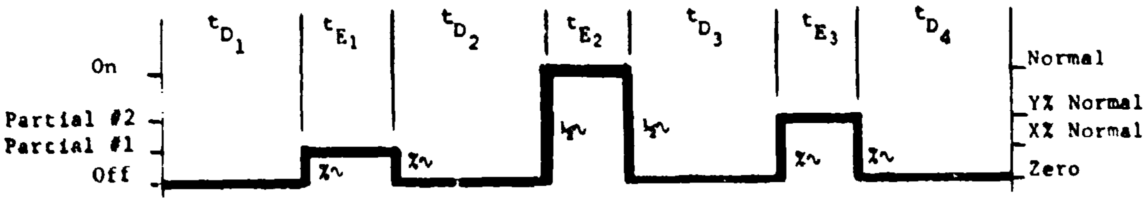
The validation of best estimate cyclic failure rates λ_C and of the cyclic to dormancy failure rate ratio $K_{C/D}$ is incomplete. This incompleteness, in general, is due to the limited amounts of data on similar equipment which not only have undergone dormancy or storage but also power on-off cycling and for which an observed failure can be validly attributed to the state during which it occurred. Much data had to be discarded because of the latter criterion.

Additionally compounding the problem is the fact that for high reliability parts and components, both a billion part-hours in dormancy and a billion part-cycles in power on-off cycling must be accumulated before the first valid failures can be expected to be observed for both states. These billion part-hours and part-cycles of data that are needed for each part are greatly increased if quantification of environmental effects, cycling rates, part quality, transient suppression, etc., is desired.

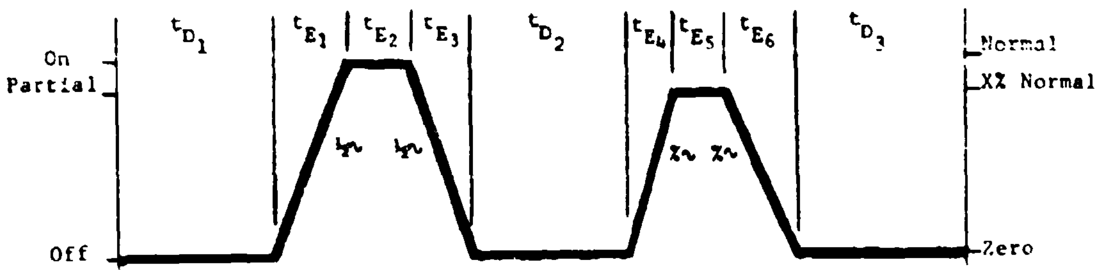
A designed experimental test approach to obtain this data on a parts level is not viable from both cost and schedule constraints. This means that a continued data collection effort on major military electronic systems is the only alternative. Consideration should be given to the structuring of an existing military data system to incorporate valid power



Example 1 Power Off-On-Off (2 Cycles)- Stepped Cycle



Example 2 Power Off-On-Off (3 Cycles)- Varying Activation Levels



Example 3 Power Off-On-Off (2 Cycles) - Slow Turn On and Turn Off and Varying Activation Levels

NOTE: Symbols are defined in Section 8 herein.

Figure 4.1.1-2 Typical Power On-Off Cycles (Idealized) Excluded on-off cycling data collection and retention requirements on a specifically designated system.

Also, an independent, low-key effort to collect power on-off cycling data, as it becomes available, should be undertaken. When such data are adequate, then appropriate data analysis and validation of cyclic failure rates and factors should be accomplished.

4.2 Previous and Current Work

The problem of on-off cycling effects on electronic equipment has been under formal study since 1948. The original investigations centered on the large number of electron tube removals which were related to filament failures. In later years, costing analyses determined that the actual number of maintenance actions was higher for continuously operated solid state equipment. This result was contrary to the idea that the increase in reliability obtained by continuous operation of electronic equipment would be accompanied by a reduction in the number of maintenance actions, but was not too surprising however, for it was well known that operating failure rates were higher than nonoperating. When equipment is cycled on and off, the proportion of off time to total calendar time is normally much higher than the on time proportion. Thus, one might suspect that the total expected number of failures during the properly selected combination of dormancy and cyclic operation will be lower than that of continuous operation.

More recently, on-off cycling studies have concentrated on the fracturing of transistor and IC internal interconnecting wires. Expansion and contraction during cycling were causing the aluminum wires to break next to the chip bond. Another problem related to cycling has been power transistor chip cracks and failures of the mounting interface. A summary of the past and present investigations of power on-off cycling problems is presented in the following paragraphs.

4.2.1 ARINC Study

A circa 1960 study was conducted by the Department of the Navy, aboard the aircraft carrier U.S.S. Forrestal on tube type electronic equipment. Four basic equipment classes were evaluated: receivers, transmitters, radar repeaters, and fire control systems. The individual assemblies in each equipment type were divided between a continuous and a cycled mode of operation and the original mode assignment was maintained throughout the test. The study results are reported in detail by Reference 4; however, the two most significant conclusions are that:

1. Equipment reliability is enhanced by continuous operation

2. The mode of operation does not induce a specific failure mechanism. Cycling and continuous operation both contribute to the causes of failure, and the respective contributions are inseparable except at the level of highly specialized laboratory analysis.

4.2.2 Planning Research Corporation (PRC) Study

PRC, under the sponsorship of the Navy Space Systems Activity, has made a comprehensive investigation of on-off cycling effects on electronic equipment operating in space. The data base encompasses approximately 40 percent of all U.S. spacecraft launched. Details of the study can be found in References 5, 6, and 7. A typical example of the magnitude of the data was the sample of 51 transmitters which had been subjected to 517 on-off cycles on each of 27 different occasions. The study has concluded that no general decision on the impact of cycling can be reached on the basis of currently available data.

4.2.3 Apollo Data

4.2.3.1 General Discussion

The Apollo data comprise three distinct sets of data involving the same kinds of electronic parts and assemblies. These data are summarized in Table 4.2.3-I. The first column contains data for the dormant mode, the second column lists data for the power on-off cycling test mode, and the third column lists data for the energized mode. These data are most useful for analysis and evaluation of the stresses produced on electronic parts and assemblies by the power on-off cycling as compared with the basic dormant mode. Similarly, a comparison may also be made of the energized with the dormant mode data.

The difficulty in separating power on-off failures from energized state failures must be realized since all these failures would previously have been charged to the energized state. In this case, all tests were supervised by cognizant scientists and engineers assigned to the project. Similarly, it was determined what failures were to be attributed to the power on-off cycling mode as well as what failures were assigned to the energized state by MIT research scientists assigned to the Apollo program.

Power on-off cycling data were obtained by turning on the equipment an average of five times a month and allowing it to remain in the energized state for about three hours after which it was turned off again. This cycling was accomplished in a room ambient temperature about 25°C. The energized on time was deemed sufficient to allow thermal equilibrium to be reached; i.e., all parts of the equipment reached the full temperature rise condition.

TABLE 4.2.3-I

Apollo Data - Storage, Power On-Off Cycling, and Energized

No.	Item	1: t_D Dormant Part-Hours $\times 10^6$	1: F_S	1: λ_D Dormant Failure Rate $\times 10^{-9}$	2: C Power On-Off Cycles $\times 10^6$	2: N_C	2: λ_C Cyclic Failure Rate $\times 10^{-9}$	3: t_E Energized Part-Hours $\times 10^6$	3: F_E	3: λ_E Energized Failure Rate $\times 10^{-5}$
1	Capacitors	1,290.2	1		12.8140	2		51.68	0	
2	Resistors	5,708.5	0		50.5638	0		69.02	0	
3	Thermistors	2.8	0		0.0168	1		0.12	0	
4	Switches	30.9	0		0.2016	4		1.04	0	
5	Thermostat	3.4	0		0.0210	0		0.17	0	
6	Transistors	1,470.1	1		13.0914	2		59.16	2	
7	Diodes	3,491.3	0		23.5284	0		151.49	0	
8	IC's	3,019.8	4		22.8522	0		126.55	2	
9	Inductive Devices	343.2	0		3.0324	9		14.68	0	
10	Relays	164.0	0		0.7980	0		6.88	4	
11	Magnetic Memory Cores	24,771.0	0		150.5280	0		1,117.00	0	
12	Rotating Devices	15.0	0		0.1008	1		0.59	0	
13	Slip Rings	5.9	0		0.0336	0		0.34	0	
14	IRIG	2.2	2		0.0126	0		0.11	13	
15	PIPA	2.2	6		0.0126	0		0.13	7	
16	Lamps	37.5	2		0.2562	1		1.12	0	
17	Fuzes	1.5	0		0.0084	0		0.09	0	
18	Connector Pins	55,437.6	0		418.3914	0		----	-	
19	Connectors	48.4	0		0.2982	0		1.58	0	
	Totals	95,845.5	16	0.17	696.5614	20	28.7	1,601.77	28	17.5
	Less 11, 16, 17, 18, and 19	15,549.5	14	0.99	127.0792	19	149.5	481.98	28	58.1
	Less 11, 14, 15, 16, 17, 18, and 19	15,545.1	6	0.39	127.0540	19	149.[illegible]	481.72	8	16.6
	Less 10, 11, 14, 15, 16, 17, 18, and 19	15,381.1	6	0.39	126.2560	19	150.[illegible]	474.84	4	8.4

The Apollo dormancy data amount to 95.8 billion part-hours experience with 16 failures resulting in a failure rate of less than 0.2×10^{-9}. When connector-pins, connectors, lamps, fuses, and magnetic memory cores are subtracted, the dormancy data amount to 15.5 billion part-hours with 14 failures. The dormancy failure rate computed with the latter data equals 0.9×10^{-9} part-hours or 0.9 fit. This dormancy rate appears to be about 2.5 times better than one would expect from parts rated as with 240 hours burn-in. However, this may be accounted for by the limited production of equipment involved and the increased attention given to quality assurance in the form of stricter standardization, more screening tests, introduction of Flight Processing Specifications (FPS's), etc.

The power on-off cycling data amount to about 697 million cycles with 20 failures and a failure rate of 28.7 per 10^9 cycles. When connector-pins, connectors, lamps, fuses, and magnetic memory cores are subtracted, the remaining cycling data amount to 127 million part-cycles with 19 failures and a failure rate of 149.5 per 10^9 cycles.

4.2.3.2 Derivation of $K_{C/D}$ Factors

From these data it becomes possible to form some idea of how much more stressful the power on-off cycling mode is when compared with the basic dormant mode. When the total data including connector-pins, etc., are compared, then $K_{C/D}$ can be established

$$K_{C/D} = \frac{20 \text{ failures} \div (0.697 \times 10^9 \text{ part-cycles})}{16 \text{ failures} \div (95.346 \times 10^9 \text{ part-hours})}$$

$$K_{C/D} = \frac{(28.7 \times 10^{-9} \text{ failure) per cycle}}{(0.167 \times 10^{-9} \text{ failure) per hour}}$$

$$K_{C/D} = 172 \text{ hours of dormancy/cycle.}$$

When the data exclude the connector-pins, connectors, lamps, and fuses, $K_{C/D}$ becomes

$$K_{C/D} = \frac{19 \text{ failures} \div (0.127 \times 10^9 \text{ part-cycles})}{14 \text{ failures} \div (15.55 \times 10^9 \text{ part-hours})}$$

$$K_{C/D} = \frac{(149.5 \times 10^{-9} \text{ failure) per cycle}}{(0.9 \times 10^{-9} \text{ failure) per hour}}$$

$$K_{C/D} = 166 \text{ hours of dormancy/cycle.}$$

And when the inertial rate integrating gyro (IRIG), and pulsed integrating pendulum accelerometer (PIPA) are excluded, $K_{C/D}$ becomes:

$$K_{C/D} = \frac{19 \text{ failures} \div (0.127 \times 10^{9} \text{ part-cycles})}{6 \text{ failures} \div (15.54 \times 10^{9} \text{ part-hours})}$$

$$K_{C/D} = \frac{(149.5 \times 10^{-9} \text{ failure}) \text{ per cycle}}{(0.4 \times 10^{-9} \text{ failure}) \text{ per hour}}$$

$$K_{C/D} \approx 374 \text{ hours of dormancy/cycle.}$$

Thus, it appears that a single power on-off cycle to thermal equilibrium and back to room ambient temperature is between about 165 to 375 (depending upon system component mix) or an average of about 270 times more stressful or effective in developing failures than one hour of dormant time. Another way of saying this is that one would expect 33 power on-off cycles as described to be equivalent to just over one year of dormancy in precipitating failures.

4.2.3.3 Derivation of $K_{E/D}$ Factors

It also becomes possible to develop an idea of how much more stressful the energized state is when compared with the basic dormant mode. When the total data including connector-pins, etc., are compared, $K_{E/D}$ is:

$$K_{E/D} = \frac{28 \text{ failures} \div (1.602 \times 10^{9} \text{ part-hours})}{16 \text{ failures} \div (95.846 \times 10^{9} \text{ part hours})}$$

$$K_{E/D} = \frac{(17.5 \times 10^{-9} \text{ failure}) \text{ per hour}}{(0.167 \times 10^{-9} \text{ failure}) \text{ per hour}}$$

$$K_{E/D} = 102.8 \text{ hours of dormancy/energized hour.}$$

Now, by excluding the connector-pin, connector, lamp, and fuse data, $K_{E/D}$ becomes:

$$K_{E/D} = \frac{28 \text{ failures} \div (0.482 \times 10^{9} \text{ part-hours})}{14 \text{ failures} \div \text{[illegible]}.55 \times 10^{9} \text{ part-hours}}$$

$$K_{E/D} = \frac{(58.1 \times 10^{-9} \text{ failure}) \text{ per hour}}{(0.9 \times 10^{-9} \text{ failure}) \text{ per hour}}$$

$$K_{E/D} = 64.6 \text{ hours of dormancy/energized hour.}$$

And finally excluding the IRIG and PIPA data, $K_{E/D}$ can be seen to decrease to:

$$K_{E/D} = \frac{9 \text{ failures} \div (0.482 \times 10^9 \text{ part-hours})}{6 \text{ failures} \div (15.54 \times 10^9 \text{ part hours})}$$

$$K_{E/D} = 41.5 \text{ hours of dormancy/energized hour.}$$

So an energized hour appears to be about 40 to 100 times more stressful or effective in developing failures than a single hour of dormancy depending upon the part and component mix within the system.

It should be noted that this $K_{E/D}$ factor of 41.5 times is about 6 or 7 times higher than the ratios of 6X and 7.5X shown in Table 3.7.1.4-I for High Reliability Classes of Parts apparently similar to those of APOLLO. The ratio of 41.5 times decreases to 21.5 when the 4 relay failures are censored and should therefore be regarded as properly indicating a trend based on a limited amount of uncensored data from one project - APOLLO. On the other hand, the $K_{E/D}$ ratios of 6X and 7.5X shown in Table 3.7.1.4-I are based on much more data from many other projects and are rank ordered with other classes of parts as well. The rates in Table 3.7.1.4-I are thus recommended for prediction work purposes since nearly 800 billion part-hours experience were involved in their development compared with about 16 billion hours for APOLLO.

4.2.3.4 Apollo Failure History

The reliability history of the Apollo Guidance Computer, Reference 6, states: "In general, many of the faults were the result of electrical transients of many types. Power-line transients and transient behavior of subsystems during power up and power down were the most common." These transients did not apparently result in the failures counted above since "A series of design changes, related to shielding and grounding, eliminated electrical interference problems..."

4.2.3.4.1 Transformers

The type of failures induced by the power on-off cycling can be well illustrated by reviewing the nine failures that occurred on transformers:

Failure Rep. No.	
023578-1	Lead magnet wire fractured where it exits the solder connection.
021618-1	Internal lead wire breakage because of poor bonding of epoxy due to flux contamination.
021612-1	Secondary magnet wire (to terminal 4) was fractured just below point of egress from coil-a tension break.
018933-1	Intermittent open in primary, cause unknown.

017352-1	Internal broken lead at terminal 7.
017291-1	Open primary caused by nick in the second stress relief loop.
017222-1	Open secondary (no added description).
014859-1	Magnet wire open near solder connection to green terminal.
--6201-1	Open in fine wire transformers - a generic problem when exposed to thermal cycling.

There are several notes to be taken from the transformer experience:

1 All the failures were opens, breaks, or fractures. Open windings in fine wire transformers are a generic problem during the manufacturing cycle when exposed to thermal cycling. No shorts were reported.

2 No fewer than three vendors were involved in supplying these transformers. All suffered some failures, so the problem cannot be placed on one manufacturer. Rather, each transformer manufacturer must take special precautions in providing stress relief loops, preventing wire nicks, assuming good soldering to terminals, etc.

3 Assuming that thermal cycling is ordinarily used as a screen to precipitate these kinds of failures in manufacturing it is possible that power on-off cycling actually represents a more rigorous form of thermal cycling. It is possible that the power on-off cycling induces local hot spot heating at potential conductivity faults resulting in wire and connection "working" due to expansion and contraction.

The next largest group of failures developed by the power on-off cycling mode is found in switches.

4.2.3.4.2 Switches

The failures reported for switches are listed:

Failure Report No.	
020420-1	Appears to be a defective contact or poor solder connection.
020321-1	Defective solder joint.

017249-1	Confirmed broken braid or open where tab connects to chip on shaft assembly of switch.
014857-1	Defective shaft assembly within push-button switch.

Observations from these data are:

1 The pattern of opens or intermittent opens appears to be continued by the power on-off cycling mode. This is sustained by the balance of failures reported on other parts as well.

2 The power on-off cycling mode appears to be a good screen for developing poor solder connection faults. Poor welds are also detected. Potential poor conductivity faults appear to be screened by power on-off cycling.

4.2.3.4.3 Capacitors

021621-1	Open due to poor internal weld within solid tantalum capacitor.
017221-1	Open due to poor internal lead solder connection.

Observations:

1 The pattern of opens is continued.

2 Poor weld and solder connections are detected by power on-off cycling. The same will be found true for poor bonds and metallization faults in semiconductors.

4.2.3.4.4 Transistors

017183-1	Open base circuit due to metallization fault within transistor.
015615-1	Open collector lead due to poor chip bonding.

Observations:

1 The pattern of opens is continued.

2 Poor connections including bonding and poor conductive paths; i.e., metallization faults are detected by the power on-off cycling mode, which produce potential conductivity problems.

4.2.3.4.5 Light, Pilot

019080-1	Open electrical connection or defective lamp.

4.2.3.4.6 Motor, Tachometer, Generator

014520-1	Poor solder connection of brown lead to inner stator magnet wire.

4.2.3.4.7 Thermistor

010469-1	Thermistor wafer fractured, probably because of unequal stresses due to a potting void.

4.2.3.5 Conclusions from Apollo Experience

1 It appears that a single power on-off cycle to thermal equilibrium for about three hours and back to room ambient temperature at about 25°C is between 165 to 375 or an average of about 270 times more stressful or effective in detecting failures than one hour of dormant time. Another way of saying this would be that we would expect 33 power on-off cycles as described to be equivalent to just over one year of dormant time in precipitating failures. It also appears an energized hour is about 40 to 100 times more stressful or effective in detecting failures than one hour of dormant time. An average $K_{E/D}$ for Apollo of 50 has been selected based on average electronic device experience of 40 to 60 hours excluding connectors, etc.

a. The data were developed over a period of about three years during which power on-off cycling was applied an average of five times a month.

b. Power on-off cycling as described appears to be about five times more stressful or effective in developing failures than the energized steady state. (Refer to paragraphs 4.2.3.2 and 4.2.3.3 herein).

2 The total failures of a system similar to Apollo and its service life constraints may now be computed:

$$F_{SL} = (\lambda_D t_D) + (\lambda_C C) + (\lambda_E t_E)$$

$$F_{SL} = (\lambda_D t_D) + (270 \lambda_D C) + (50 \lambda_D)$$

$$F_{SL} = (t_D + 270C + 50 t_E) \lambda_D \quad \text{(Equation 4.2.3.5-1)}$$

when $t_E \rightarrow 0$,

then Equation 4.2.3.5-1 reduces to:

$$F_{SL} = (t_D + 270C)\ \lambda_D \qquad \text{(Equation 4.2.3.5-2)}$$

3 The power on-off cycling state as described herein appears to be particularly effective in precipitating failures caused by potential conductivity faults. This is well illustrated:

a. No fewer than three vendors were involved in transformer fault history of opens, breaks, fractures or bad solder joints where the largest number of failures was found. All manufacturers need to be careful with stress relief loops, wire nicks, good solder joints at terminals, etc. Open windings in fine wire transformers is a generic problem during the manufacturing cycle when exposed to thermal cycling. However, power on-off cycling may be more rigorous in that it induces hot spot heating at faults resulting in wire and connection "working" due to expansion and contraction especially at potential poor conductivity fault points.

b. The tendency to precipitate potential poor [illegible]vity fault points was also noted in switches with poo[illegible]der joints, in capacitors with bad internal welds and solder joints, in transistors with poor bonds and bad metallization, and in a tachometer-generator with a poor solder connection.

This effect of power on-off cycling is of special interest because there is no present method known which facilitates checking for poor solder or weld joints or other potential conductivity faults in a system other than continuous monitoring during vibration testing, which is both difficult and expensive.

4.2.4 SPRINT Data

The data accumulated on SPRINT missile GRA-8 and its Launch Prep Equipment (LPE) are amenable to establishing power on-off cycling factors. Over a continuous 472 day period, detail test records were kept during horizontal marriage tests, Electro Magnetic Interference Tests, and other system laboratory tests. Table 4.2.4-I summarizes these data for the dormancy, power on-off cycling, and fully energized states.

TABLE 4.2.4-I

SPRINT GRA-8 Missile and LPE Data - Dormancy Power On-Off Cycling, and Energized

GRA-8	Dormancy t_D Part-Hours $\times 10^9$	Dormancy F_D	On-Off Cycles N	On-Off Cycles F_C	Energized t_E Part-Hours $\times 10^9$	Energized F_E
Missile Electronics	0.128879	0	4,391	0	0.0005	0
LPE Electronics	0.074889	0	8,970	0	0.0004	0
Totals	0.203768	0	6,082 (1)	0	0.0009	0

(1) Quantities of cycles are not additive because GRA-8 Missile and LPE on-off cycles are not mutually exclusive, so a weighted value must be determined as follows:

$$\left(\frac{128}{203}\right)\left(4{,}391\right) + \left(\frac{75}{203}\right)\left(8{,}970\right) = 2768 + 331 = 6{,}082$$

Using the data of Table 4.2.4-I, the value $K_{C/D}$ may be calculated using Equation 1.1.2-9 providing $r_S + r_D \geq 0.99$. Checking for $r_S + r_D \geq 0.99$, it is found that:

$$r_S + r_D = 1 - r_E$$

$$r_S + r_D = 1 - \frac{0.0009 \times 10^9}{0.203758 \times 10^9 + 0.0009 \times 10^9}$$

$$r_S + r_D = 0.9956; \text{ hence,}$$

Equation 1.1.2-9 is applicable and yields the following value for $K_{C/D}$:

$$\lambda_{SL} \approx (1 + K_{C/D} N_C) \lambda_D$$

$$\frac{0 + 0 + 0}{0.204668 \times 10^9} \approx \left[1 + \left(K_{C/D}\right)\left(\frac{6,082}{472 \times 24}\right)\right]\left[\frac{6}{2.608 \times 10^9}\right]^*$$

$$4.886^{**} \approx \left(1 + 0.537\ K_{C/D}\right)\left(2.300\right)$$

$$K_{C/D} < 2.1$$

* Demonstrated λ_D for SPRINT electronics.

** Assumes 1 failure for λ_{SL} computational purposes.

The derived $K_{C/D}$ value of less than 2.1 for SPRINT electronics leads to interesting conjecture on why such a difference between this and the $K_{C/D}$ value of 172 observed for Apollo (Reference Paragraph 4.2.3.2 herein). This difference can be examined by constructing a matrix of all those factors affecting power on-off cycling for both systems and examining for significant differences. Table 4.2.4-II is this comparison matrix and shows **two significant differences**.

4.2.5 Other Studies

Between 1970 and 1972, the U.S. Air Force conducted an investigation to determine if maintenance costs could be decreased by reducing needless ground operation of aircraft electronic equipment. The results of this study are detailed in References 9 and 10. A reduction in ground operating time was found to cause a decrease in failures. Therefore, it was concluded that it might be possible to effect maintenance savings of 13 percent to 17 percent with the use of a Ground Automatic Disconnect System (GADS). Collected data from aircraft with and without GADS was inconclusive as to the impact of cycling on the equipment.

A NASA ALERT (Reference 11), identified a transistor failure mode that was directly related to power on-off cycling. Part failures were caused by the thermal compression bonding process as used on the 1 mil diameter aluminum lead wires interconnecting the 2N2222A transistor chip and header. The small wires were fracturing next to the thermal compression bond on the chip. The bonding process reduced the wire diameter at the bond which became the weak point in the wire when it was subjected to expansion and contraction during power cycling. Subsequent tests have demonstrated that this failure mode is not so likely to occur when wires are ultrasonically bonded to chips. Use of gold wire or greater than 0.003 diameter aluminum wire also alleviates the problem.

TABLE 4.2.4-II

Power On-Off Cycling Comparison Matrix Apollo and SPRINT Electroni

CYCLING FACTORS	APOLLO	SPRINT
1. Part Types and Mix	Type -% Resistors - 37 Capacitors - 8 Diodes - 23 Transistors - 9 IC's - 20 Other - 3	Type -% Resistors - 54 Capacitors - 17 Diodes - 11 Transistors - 12 IC's - 3 Other - 3
2. Part Class or Quality (C_Q)	168 to 240 hour burn-in + standardization + limited production + extra screens + process specs	240 hour burn-in + standardization + controlled lines + extra screens + process specs
3. Cyclic Rate (C_{N_C})	≈ 0.007 cycles/hour	≈ 0.537 cycles/hour
4. Temperature (C_T)		
a. Initial Ambient	20 - 25°C	20 - 25°C
b. Temperature Stabilization	3 hours power on Temperature stabilized and reaches peak effect	10 seconds power on Temperature not stabiliz nor reaches peak effec
c. Thermal Lag	Not Applicable	Not Applicable
d. Derating	Resistors 50% Capacitors Tantalum 25% Ceramic 60% Diodes 50 - 75% Transistors 50 - 75% IC's - 15V devices used at 5V	Resistors 30 - 4 Capacitors 50% Diodes 40 - 7 Transistors 40 - 6 IC's - Below voltage
e. Applied Power	Unknown	Unknown
5. Transient Suppression (C_{TS})	Parts Derated ≈ 50% Designed In, Details Not Avail.	Parts Derated ≈ 50% Designed In, Details Not
6. Environment (C_E)	Laboratory	Laboratory

TABLE 4.2.4-II

Cycling Comparison Matrix Apollo and SPRINT Electronics

POLLO	SPRINT	SIGNIFICANT DIFFERENCE Yes	No	Unknown
-%	Type -% ± T%	± T>10%	± T<10%	
rs - 37	Resistors - 54 45 ± 9%		X	
ors - 8	Capacitors - 17 12 ± 4%		X	
- 23	Diodes - 11 17 ± 6%		X	
tors - 9	Transistors - 12 11 ± 2%		X	
- 20	IC's - 3 12 ± 9%		X	
- 3	Other - 3 3 ± 0%		X	
240 hour burn-in	240 hour burn-in		X	
ardization	+ standardization		X	
ed production	+ controlled lines		X	
screens	+ extra screens		X	
ss specs	+ process specs		X	
cycles/hour	≈ 0.537 cycles/hour	X		
°C	20 - 25°C		X	
power on	10 seconds power on			
ture stabilized	Temperature not stabilized			
aches peak effect	nor reaches peak effect	X		
licable	Not Applicable		X	
rs 50%	Resistors 30 - 40%		X	
ors	Capacitors 50%		X	
lum 25%				
ic 60%				
50 - 75%	Diodes 40 - 70%		X	
tors 50 - 75%	Transistors 40 - 60%		X	
15V devices used at 5V	IC's - Below voltage		X	
	Unknown			X
erated ≈50%	Parts Derated ≈50%			
d In, Details Not Avail.	Designed In, Details Not Avail.		X	
ory	Laboratory		X	

Comprehensive on-off cycling tests have been performed by RCA on a large sample of 2N3055 power transistors. The results of this program are described in Reference 12. Two separate failure modes were observed that were precipitated by cycling. Below 10^4 cycles, cracked pellets were observed but this problem was attributed to process variations which were subsequently brought under control. Between 10^4 and 10^5 cycles, a wearout type mechanism resulting in pellet lifting was noticed. The interface consisted of nickel/tin materials which were expanding and contracting at different rates during the cycling. An appreciable amount of shearing was taking place which caused fatigue failures at the contact point. This problem was not considered critical because the failures were occurring well beyond the normal use of the device.

Unpublished studies by IBM have determined that equipment operated a large percentage of its service life is expected to exhibit a greater number of failures than the same equipment operated a small percentage of its service life. A problem arises when the using services count all observed failures against operating time only. This results in a misleading operating failure rate, because it shows more failures per operating hour. This situation has an important impact on cost of maintenance. In general, continuously operated systems have a higher incidence of failure which results in a higher overall cost than a properly selected dormant system. This is because of increased organizational and maintenance costs. IBM has observed very few turn-on failures with their military computer equipment, which employs voltage sensing. Logic turn-on is delayed until power has stabilized, and transient suppression circuitry is also utilized.

4.3 Factors and Models

4.3.1 Cyclic Failure Rate (λ_C) and Models

There are several factors which contribute to or influence field cyclic failure rates (λ_C) of electronic systems. Based upon observations of power on-off cycling data from four major electronic systems, these contributors are not always independent of one another. Rather than depending upon system design and duty cycle characteristics, a contributor can be seen in one system to influence another contributor, but in another electronic system with a short on-time, this influence is not exhibited. This means great caution and care must be exercised in construction of any power on-off cycling mathematical model.

The approaches taken by Martin Marietta must be viewed as a first step. Initial definitions of terms, grouping of factors, construction of the initial model, and partial quantification of the factors have been accomplished. These must be considered as the starting point from which additional improvement can be made as more and better field power on-off cycling data become available.

4.3.1.1 General Part, Component, or System Model for λ_C

In this initial modeling attempt, the contributing factors of λ_C have been reviewed. The dependent ones were determined and grouped into a single C_i factor.

As a result, only the basic cyclic failure rate and five modifying factors remain. The initial λ_C model, its terms, and derivation are:

$$\lambda_C = \lambda_{CB} \prod_{i=1}^{n=5} C_i \qquad \text{(Equation 4.3.1-1)}$$

or

$$\lambda_C = \lambda_{CB} C_Q C_{N_C} C_T C_{TS} C_E \qquad \text{(Equation 4.3.1-2)}$$

where λ_C = field cyclic failure rate of part, component or system

λ_{CB} = base cyclic failure rate as related to initial temperature state

C_Q = part quality (grade or class) factor; this factor is a function of the manufacturing process and subsequent controls imposed such as Group A and B electrical tests, special screens, or burn-in on individual parts and components.

C_{N_C} = cycling rate factor; this factor is a function of the expected cycling rate (normally expressed as cycles per hour); the cycling rate can be estimated for a given system as:

$$N_C = \frac{N}{t_{CL}}$$

that is, the total number of actual or anticipated power on-off cycles that will occur on that item during its entire service life expressed in hours. This factor represents all non-temperature related effects such as mechanical shock, wear, vibration, material fatigue, creep, or other cyclic induced stresses.

C_T = temperature effect factor; this is a complex factor comprised of several sub-factors which are dependent:

1 Initial temperature state

2 Applied electrical energy versus part derating with resultant thermal stresses

3 Thermal lags at turn-on and at turn-off

4 Temperature stabilization state (time to and time at)

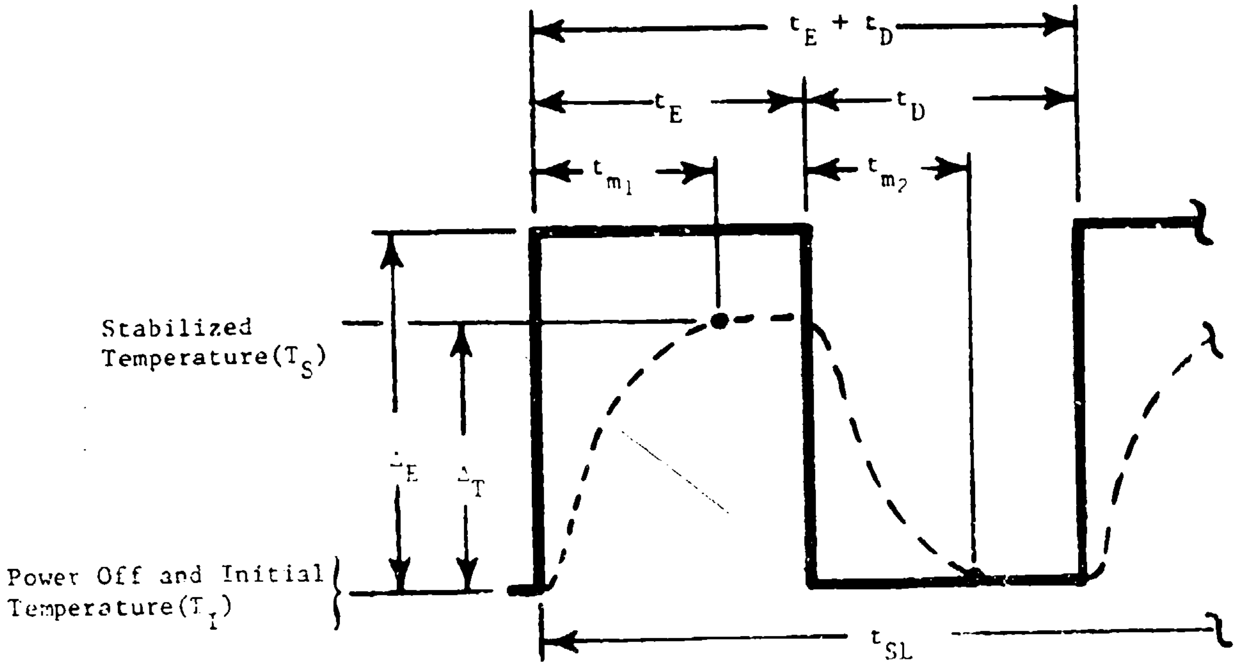
5 Residual temperature effects (a function of time between cycles).

Refer to Figure 4.3.1-1 and related discussion for a more detailed explanation.

C_{TS} = transient suppression factor; this factor is a function of the degree to which transient suppression circuitry and design have been provided to eliminate or reduce damaging voltage or current transients at power turn-on or turn-off. These transients may either be line conducted or induced by internal or external sources.

C_E = environmental mode factor; this factor is an adjustment factor for the various environments in which power on-off cycling occurs.

The subfactors of C_T are sometimes dependent and sometimes independent of one another. This can be better understood by studying Figure 4.3.1-1. This figure shows the initial temperature state (T_I) as room ambient in the power-off condition. When the power is turned on, the internal temperature rises at a rate dependent on applied power, part derating and packaging, etc. The temperature rises until it reaches a stabilized temperature (T_S) at time t_{m_1} providing that $t_{m_1} \geq t_E$. When power is turned off, the internal temperature decreases at a rate dependent on heat dissipation paths. The temperature decreases until it again reaches room ambient at time t_{m_1} providing $t_{m_2} \leq t_D$. The terms t_{m_1} and t_{m_2} are thermal lag times and their values are contingent upon energy levels, part derating, equipment configuration (density, heat sinks, construction, etc.), and ancillary cooling. The interdependency of the C_T factor contributors can now be readily seen.



NOTES:

——— Energy Profile for Power On-Off Cycle

- - - Temperature Profile for Power On-Off Cycle

Δ_E = Energy Change (Power Off to Power On or Vice Versa)

$\Delta_T = T_S - T_I$ = Maximum Temperature Change

If $t_{m_1} \geq t_E$, then full Δ_T is not realized and this reduces temperature effect.

If $t_{m_2} \geq t_D$, then residual temperature effects increase temperature effect.

Figure 4.3.1-1 General Diagram of Contributors to the Temperature Effect Factor C_T During Power On-Off Cycling

4.3.1.2 General Electronic Part, Component, or System Model for Power On-Power Off Reliability Prediction

The probability of success, or reliability, of a part, component, or system can be expressed by the exponential relationship:

$$P_{SC} = R_C = e^{-F_C} \qquad \text{(Equation 4.3.1.2-1)}$$

Substituting in equation 1.1.2-3 (where λ_C is constant with cycles), Equation 4.3.1.2-1 becomes:

$$R_C = e^{-\lambda_C C} \qquad \text{(Equation 4.3.1.2-2)}$$

4.3.1.3 General Electronic Part, Component, or System Model for Service Life Prediction

Based upon the earlier discussion contained in Section 1.1.1, Interrelationship, a service life model can be expressed in terms of the exponential relationship:

$$P_{SL} = R_{SL} = e^{-F_{SL}} \qquad \text{(Equation 4.3.1.3-1)}$$

The negative F_{SL} term of Equation 4.3.1.3-1 can be represented by several expanded expressions which account for service life. Equations 1.1.2-4, 1.1.2-5, 1.1.2-7, or 1.1.2-9 are just a few. A detailed discussion and examples of the expansion of an F_{SL} term based on typical service life cycles are given in Section 5.0.

4.3.2 Preliminary Quantification of λ_C Factors

The data contained in Section 4.4 has been used to derive preliminary quality improvement factors, C_Q values for the power on-off cycling environment. These values are shown in Table 4.3.2-I and relate to the amount of improvement which can be expected in going from Military Standard to high reliability quality levels.

For example, the cycling failure rate of a high reliability type integrated circuit is expected to be 1/14,800 that of a comparable military standard device. The overall factor for electronic parts appears to be about 1/3,300. In studying the table, it can be observed that screening and burn-in on integrated circuits and transistors are much more effective in removing parts with inherent weakness to cycling effects than is the case with resistors, diodes and magnetics. Temperature cycling is well known to be a beneficial screen for microelectronics and transistors. The reason for this efficiency can be related to the thermal environment which is a major contributor to power on-off cycling failures.

A high reliability system which uses a large percentage of integrated circuits as opposed to discrete transistors would have a higher reliability because integrated circuits can withstand cycling effects about 20 to 1 better than transistors.

TABLE 4.3.2-I

Estimated Values of C_Q for Various Part Types

Part Type	C_Q Military Standard to High Reliability*
Integrated Circuits	14,800 to 1
Transistors	4,200 to 1
Capacitors	1,500 to 1
Resistors	700 to 1
Diodes	500 to 1
Inductive Devices	100 to 1
Average C_Q (total experience)	3,300 to 1

*Normalized to high reliability value for same part type.

The temperature effect factor C_T exerts a major influence over the model because approximately 90 percent of power on-off cycling induced failure modes appear to be related to temperature change and resulting expansion and contraction which creates malfunctions in inherently weak electronic parts. As has been seen in Section 4.2.4, this factor can range from 1 to greater than 200. Further quantification of C_T should be obtained by properly designed experiments in which certain critical influence factors would be varied while others would be held constant.

Short duration power on-off transients in the order of nanoseconds are a well known problem with inductive and many other types of electronic circuitry. Since these transients are typically less than twice the normal steady state operating parameters, derating of electronic parts by 50 percent or more can usually be expected to effectively combat the transient problem. If larger transients are observed, special transient suppression circuitry can be employed. Systems evaluated by this study which had been severely derated, i.e., operating at about 10 percent of the part specification ratings, do not exhibit failures which can be attributed to transients. Thus, it appears that there are very few damaging transients at levels an order of magnitude greater than normal operation. The effects of transients and their interrelationship with power on-off cycling as well as part derating are thus included in the model. The actual quantification of the transient suppression factor C_{TS} as well as the base cyclic failure rate λ_{CB} is not possible from currently available data. Quantification of C_{TS} and λ_{CB} requires comprehensive statistically controlled laboratory experimentation.

The final factor for λ_C is C_E. Almost all the usable data collected and analyzed came from laboratory conditions. This fact precluded determining C_E values from the power on-off cycling data; instead, C_E values have been derived from energized experience and assumed to be applicable to power on-off cycling. Table 4.3.2-II presents the C_E values for various environments.

TABLE 4.3.2-II

Estimated Values of C_E for Various Environments

(These modifiers apply only to the cyclic part failure rate. If an overall part failure rate including dormancy and operating is to be determined, then caution must be exercised not to double count environmental effects).

Environment	C_E
Satellite	0.1
Laboratory	1.0
Ground, Fixed	5.0
Ground, Mobile	7.5
Aircraft, Manned	6.5
Aircraft, Unmanned	15.0
Missile, Checkout	5.0
Missile, Flight	25.0
Missile, Ground Launch*	50 - 100*
Missile, Airborne Launch*	100 - 1000*
Shipboard, Surface	-
Shipboard, Submarine	10.0

* These C_E values apply only to the first few seconds of missile launch. Missile flight C_E then becomes 25.0.

4.4 Failure Rates and Tables

4.4.1 Failure Rates λ_C For Laboratory Environment

The power on-off cycling study resulted in the collection of approximately 177 million part-cycles of data on Military Standard parts and 118 billion part-cycles on high reliability (TX, ER, Class A & B) parts. Vendors also supplied 24 million part-cycles of data on microelectronic devices. Almost all of the data are from laboratory environmental conditions.

The best estimates of λ_C for Military Standard parts in the laboratory environment have been made and are contained in Table 4.4.1-I. Unfortunately the small quantity of data and observed failures permit only a "less than" best estimate for all components except low power NPN and high power NPN transistors. Much additional data are required in the Military Standard category to permit better estimate of the λ_C values or to allow construction of a ranking analysis table similar to those done for dormant failure rates.

Estimates of λ_C for high reliability grades of parts are shown in Table 4.4.1-II. These data also apply to the laboratory environment. Again many parts types have not accumulated sufficient experience in part-cycles or failure to obtain a close estimate of λ_C.

Finally vendor supplied information on integrated circuits has been compiled. Table 4.4.1-III presents these data for informational purposes only and it applies to the laboratory environment also.

4.4.2 Cyclic Failure Rate and Ratio Tables

4.4.2.1 Microelectronic Device λ_C Table

The data available for the construction of Table 4.4.2.1-I are for the laboratory environment. The data for the integrated circuits are from Tables 4.4.1-I, 4.4.1-II, and 4.4.1-III. No data were available for hybrid devices. Therefore, conservative engineering judgment tempered by similarity of device ratios in dormancy to those known for power on-off cycling, was used to fix device locations for the various devices for MIL-STD-883 Class A, B, C and non MIL-STD-883.

4.4.2.2 Cyclic Failure Rate (λ_C) Table - High Reliability Parts

The data from Table 4.4.1-II have been reviewed for ranking. Insufficient data for ranking λ_C by parts categories exist so a general λ_C ranking table has been prepared. Table 4.4.2.2-I is this table and applies to the laboratory environment.

TABLE 4.4.1-I

Observed Power On-Off Cycling Data, Military Standard Parts

Part Type	C Part-Cycles x 10^6	F_C Failure	λ_C Failure Rate (per billion part-cycles)
Antennas and Peripheral Equipment	0.171	0	<5848
Antennas	0.013	0	<76923
Attenuators	0.026	0	<38462
Circulators, 4 Port	0.044	0	<22727
Couplers, Antenna	0.053	0	<18868
Couplers, Directional	0.035	0	<28571
Capacitors	6.758	0	<148
General Class	0.534	0	<1873
Ceramic	0.640	0	<1563
Glass	3.152	0	< 317
Mica	0.065	0	<15625
Paper	0.320	0	<3125
Plastic	0.272	0	<3676
Tantalum, Foil	0.288	0	<3472
Tantalum, Solid	1.120	0	<893
Tantalum, Wet	0.368	0	<2717
Choppers	0.016	0	<62500
Filters	0.011	0	<90909
Fuses	0.104	0	<9615
Relays	0.923	0	<1083
Resistors	48.231	0	<21
Carbon Composition	14.384	0	<70
Metal Film	32.135	0	<31
Wirewound	0.960	0	<1042
Variable	0.752	0	<1330
Semiconductors	118.156	242	2048
Diodes	24.382	0	<41
Low Power	22.818	0	<44
High Power	0.112	0	<8929
Zener	1.452	0	<689
Transistors	93.774	242	2581
Low Power	92.794	241	2597
NPN	82.320	241	2928
PNP	10.474	0	<95
Medium Power	0.304	0	<3289
NPN	0.048	0	<20833
PNP	0.256	0	<3906
High Power	0.676	1	1479
NPN	0.404	1	2475
PNP	0.272	0	<3676
Surge Arrestors, Spark Gap	0.322	0	<3106
Switches	1.200	0	<833
Transformers	0.837	0	<1195
TOTAL	176.729	242	1369

TABLE 4.4.1-II

Observed Power On-Off Cycling Data, High Reliability Parts

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
Capacitor	20101.477	2	0.10
Aluminum	0.269	0	<3717.47
Ceramic	9539.056	0	<0.10
Glass	277.905	0	<3.60
Metal Film	0.012	0	<83333.33
Mica	0.720	0	<1388.89
Mica, Reconstituted	0.017	0	<58823.53
Mylar	0.705	1	1418.44
Paper	0.044	0	<22727.27
Plastic/Paper	0.012	0	<83333.33
Polystyrene	0.096	0	<10416.67
Tantalum, General Class	10273.777	0	<0.10
Tantalum, Foil	0.053	0	<18867.92
Tantalum, Solid	8.742	1	114.39
Tantalum, Wet	0.012	0	<83333.33
Variable	0.057	0	<17543.86
Connective Devices	9493.722	0	<0.11
Connectors	9075.331	0	<0.11
Connector Pins	418.391	0	<2.39
Crystals	0.035	0	<28571.43
Electromechanical Devices	0.195	1	5128.21
Counters	0.012	0	<83333.33
Fans, Axial	0.026	0	<38461.54
Fans, Centrifugal	0.017	[illegible]	<58823.53
Motors	0.044	1	22727.27
Blower	0.008	0	<125000.00
DC	0.004	0	<250000.00
Servo	0.016	1	6[illegible]0.00
Torque	0.016	0	<6250[illegible].00
Resolvers	0.063	0	<15873.02
Slip Rings	0.033	0	<30303.03
Filters	0.004	0	<250000.00
Heaters	0.012	0	<8333.33
Illuminating Devices	11.128	23	2066.86
Lamps	2.863	21	7334.96
General Class	2.608	20	7668.71
Annunciator	0.008	0	<125000.00
Electroluminescent	0.155	0	<6451.61
Incandescent	0.092	1	10869.57
Light Emitting Diode	8.265	2	241.98

TABLE 4.4.1-II
(continued)

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
Inductive Devices	553.830	0	<1.81
Chokes	0.016	0	<62500.00
Coils	499.090	0	<2.00
General Class	498.200	0	<2.01
Radio Frequency	0.890	0	<1123.60
Delay Lines	54.304	0	<18.41
Inductors	0.248	0	<4032.26
Reactors	0.172	0	<5813.95
Inertial Guidance Devices	0.016	0	<62500.00
Accelerometer	0.008	0	<125000.00
Gyros	0.008	0	<125000.00
Magnetic Cores	150.528	0	<6.64
Oscillators, Isolator	0.004	0	<250000.00
Relays	0.798	0	<1253.13
Resistors	36119.508	1	0.03
General Class	1.733	0	<577.03
Carbon Composition	122.312	0	<8.18
Carbon Film	0.185	0	<5405.41
Metal Film	32309.048	0	<0.03
Thermistor	0.033	1	30303.03
Thermal Resistor	16.380	0	<61.05
Tin Oxide	39.110	0	<25.57
Wirewound, General Class	3590.500	0	<0.28
Wirewound, Power	11.502	0	<86.94
Wirewound, Precision	0.040	0	<25000.00
Wirewound, Heater Element	0.040	0	<25000.00
Variable, General Class	0.394	0	<2538.07
Variable, Metal Film	1.031	0	<969.93
Variable, Wirewound	27.200	0	<36.76
Semiconductors	51066.492	5	0.10
Diodes	13226.508	0	<0.08
General Class	0.022	0	<45454.54
Low Power	10928.512	0	<0.09
Medium Power	0.483	0	<2070.39
High Power	463.399	0	<2.16
Tunnel	0.331	0	<3021.15
Zener	1833.761	0	<0.55
Integrated Circuits	29721.597	0	<0.03
Digital	28267.103	0	<0.04
Class A	22.717	0	<44.02
Class B	28244.386	0	<0.04

TABLE 4.4.1-II
(continued)

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
Linear	1454.494	0	<0.69
Class A	0.134	0	<7462.69
Class B	1454.360	0	<0.69
Transistors, Silicon	8118.387	5	0.62
General Class	0.008	0	<125000.00
Low Power	7523.568	0	<0.13
NPN	4571.260	0	<0.22
PNP	2952.308	0	<0.34
Medium Power	3.936	0	<254.07
NPN	2.907	0	<344.00
PNP	1.029	0	<971.82
High Power	589.444	5	8.48
NPN	507.841	5	9.85
PNP	81.603	0	<12.25
Field Effect	1.085	0	<921.66
SCR	0.342	0	<2923.98
NPNP	0.161	0	<6211.18
PNPN	0.181	0	<5524.86
Unijunction	0.004	0	<250000.00
Switches	0.550	4	7272.72
General Class	0.201	4	19900.50
Electronic	0.053	0	<18867.92
Indicator Light	0.053	0	<18867.92
Inertial	0.008	0	<125000.00
Humidity Control	0.017	0	<58823.53
Pressure	0.013	0	<76923.08
Thermostatic	0.161	0	<62111.80
Toggle	0.044	0	<22727.27
Temperature Sensors	0.004	0	<250000.00
Thermostats	0.021	0	<47619.05
Transformers	138.618	9	64.93
General Class	138.201	9	65.12
Audio Frequency	0.017	0	<58823.53
Power	0.111	0	<9009.01
Pulse	0.066	0	<15151.52
Radio Frequency	0.215	0	<46511.63
Saturable	0.008	0	<125000.00
Tubes, Sprytron	0.017	0	<58823.53
Video Signal Detectors	0.026	0	<38461.54
TOTAL	117636.985	45	0.38

TABLE 4.4.1-III

Vendor Integrated Circuit Power On-Off Cycling Test Data

Part Type	C Part-Cycles x 10^6	F_C Failures	λ_C Failure Rate (per billion part-cycles)
General Class	1.750	0	<571
Digital	22.418	10	446
Non MIL-STD-883	2.748	3	1092
Class B	16.900	0	<59
Class C	2.770	7	2527
Linear	0.613	1	1631
Non MIL-STD-883	0.291	1	3436
Class C	0.322	0	<3106
TOTAL	24.781	11	444

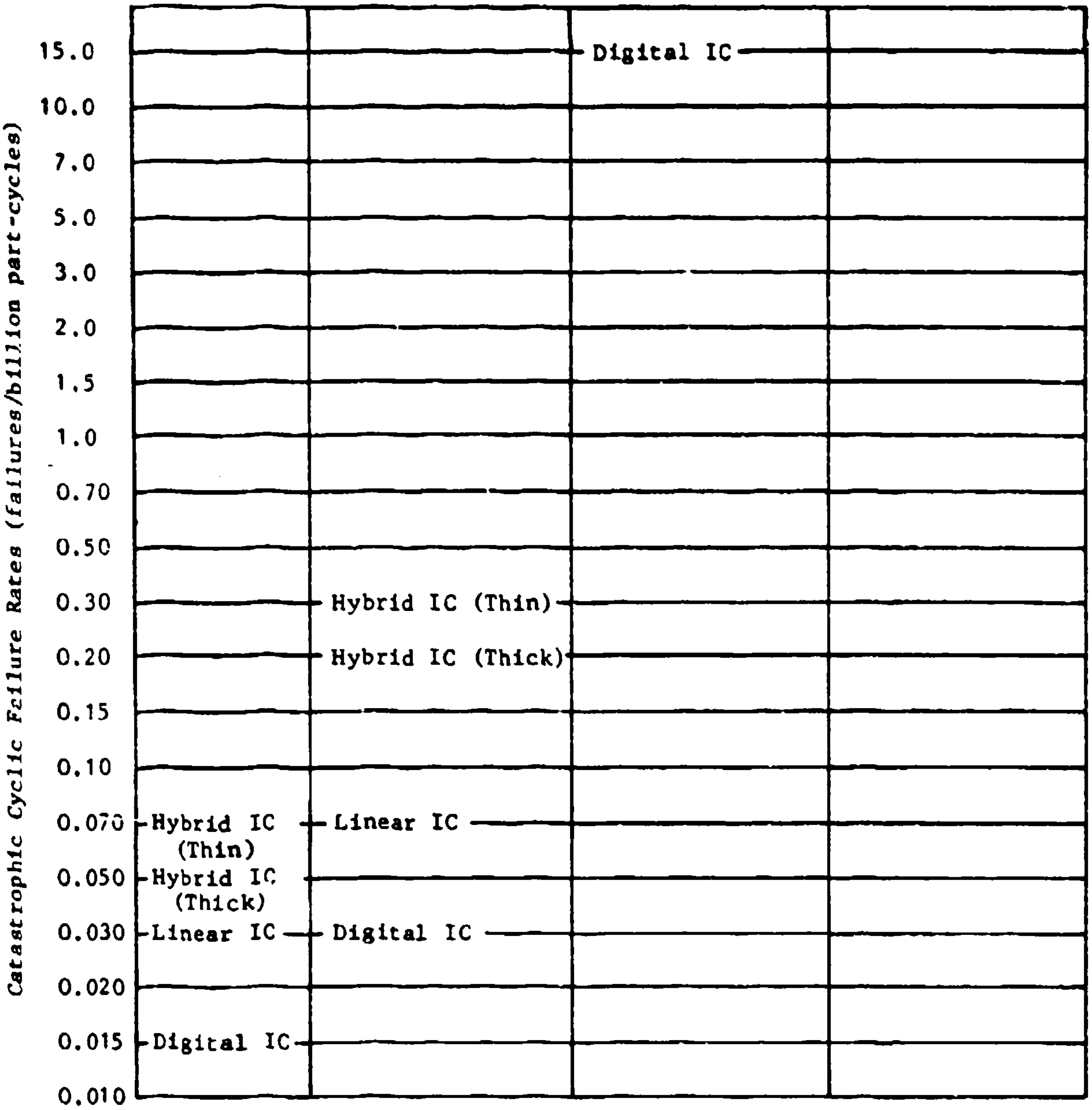
TABLE 4.4.2.1-I

Catastrophic Cyclic Failure Rates (λ_C) For Microelectronic Devices

1. Environment - **equipment laboratory operation & satellite**
2. Cyclic Rate - 6 cycles (or less) per 24 hours
3. Time On - sufficient for temperature stabilization
4. Derating - 50 percent or greater on voltage

Catastrophic Cyclic Failure Rates (failures/billion part-cycles)	Military - Standard - 883			Non MIL-STD-883
	Class A	Class B	Class C	
30,000				
20,000				Hybrid IC (Thin)
15,000				
10,000				Hybrid IC (Thick)
7,000				
5,000				
3,000				Linear IC
2,000				
1,500				
1,000				Digital IC
700				
500				
300				
200			Hybrid IC (Thin)	
150				
100			Hybrid IC (Thick)	
70				
50			Linear IC	
30				
20				

TABLE 4.4.2.1-I
(continued)



Class A - Devices intended for use where maintenance and replacement are extremely difficult or impossible, and reliability is imperative.

Class B - Devices intended for use where maintenance and replacement can be performed, but are difficult and expensive, and where reliability is imperative.

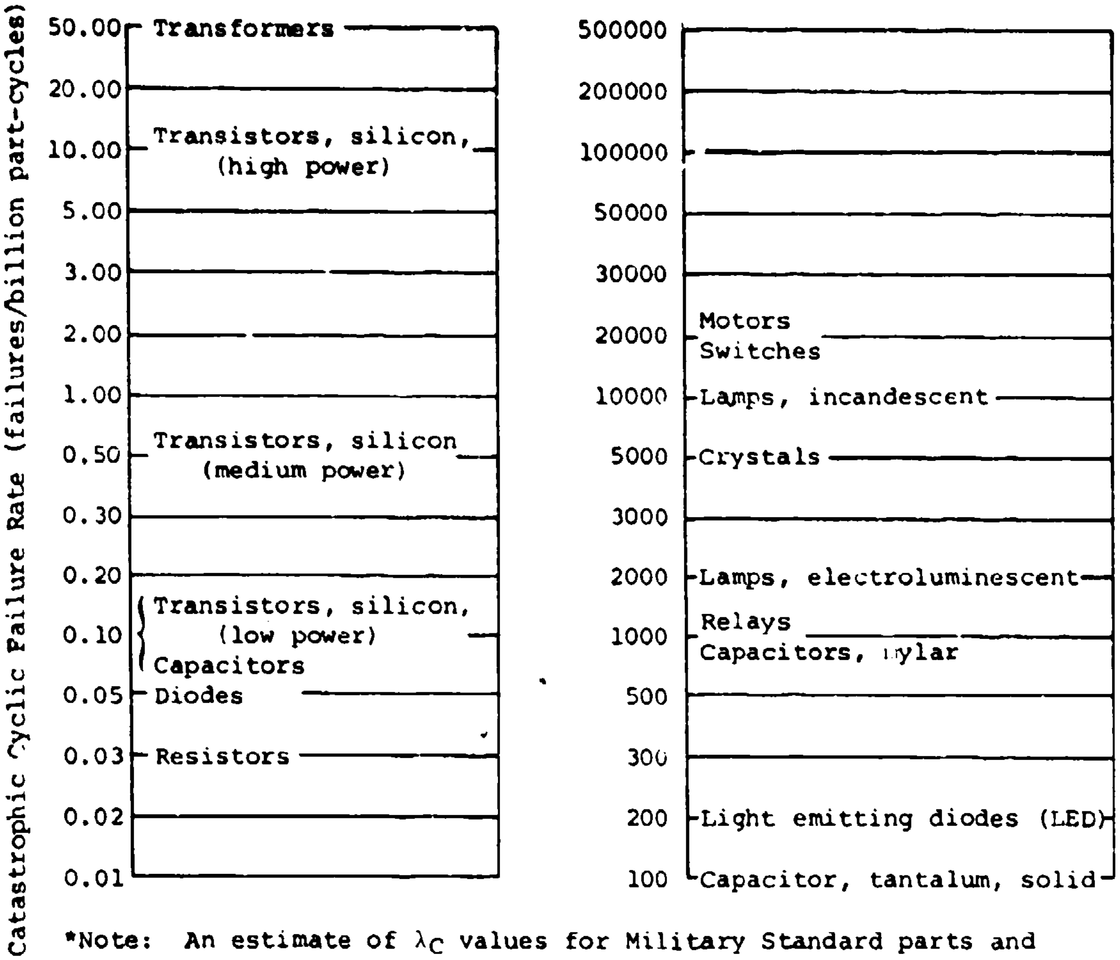
Class C - Devices intended for use where maintenance and replacement can be readily accomplished and down time is not a critical actor.

Non MIL-STD-883 - Devices are not intended for military application, but data have been included for informational purposes only.

TABLE 4.4.2.2-I

Catastrophic Cyclic Failure Rates (λ_C) For High Reliability Parts and Components*

1. Environment - **equipment laboratory operation & satellite**
2. Cyclic rate - 6 cycles (or less) per 24 hours
3. Time on - sufficient for temperature stabilization
4. Derating - 50 percent or greater on electronic devices



*Note: An estimate of λ_C values for Military Standard parts and components under similar environmental, cyclic rate, duty cycle, and derating conditions can be made by applying the appropriate C_Q values of Table 4.3.2-I to the values shown in this Table.

4.4.2.3 Construction of $K_{C/D}$ Table

The construction of a preliminary $K_{C/D}$ table has been attempted based on several billion hours of dormancy and cycling experience on identical parts in identical equipment and on the engineering judgement of specialists who applied a ranking analysis technique to the various categories of parts using a 50 percent decade scale.

Parts descriptions, as available, were studied along with failure modes and mechanisms. The raw data were censored so that it could be applied judiciously in the construction of Table 4.4.2.3-I. In so doing, several categories had to be combined or discarded; for example, connectors, listed in column 6, are actually comprised of five smaller subcategories which contained too little data to be considered separately.

In those cases for which no failures were observed, then a most likely range with upper and lower limits was derived. This aided in rough ordering each part or component with respect to the others.

Some apparent anomalies may be observed. For instance, the ranking of the light emitting diode (LED) is much higher than that of low or medium power diodes, which are of similar construction. But on the basis of two independent cyclic LED failures, a lower $K_{C/D}$ value cannot be justified at this time.

Limitations of Table 4.4.2.3-I are many, of which a few are:

1 The ratio $K_{C/D}$ can be assumed to be approximately equal to $K_{C/S}$ because no significant statistical difference has been found between λ_S and λ_D.

2 The cyclic rate will affect the ratios and this chart is for a slow cyclic rate of not more than 6 times per day and in which temperature stabilization occurs after each turn-on and turn-off.

3 The transient suppression protection provided is consistent with good design practices.

4 That only higher quality grades of parts are represented, such as TX, ER, or Class A and B for microelectronics.

TABLE 4.4.2.3-I

$K_{C/D}$ Ratios for High Reliability Parts and Components*

1. Environment - equipment laboratory operation
2. Cyclic rate - 6 cycles (or less) per 24 hours
3. Time on - sufficient for temperature stabilizatio
4. Derating - 50 percent or greater on devices in col

Cyclic Failure Rate Ratio for $K_{C/D}$ In Hours/Cycle	Resistors and Resistive Devices 1	Capacitors 2	Semiconductors and Microelectronic Devices 3	Transformers and Inductors 4	Elect and D
2000					
1000				Transformers	
500			Hybrid IC (thin film)		Switch
200		Tantalum, wet, foil Tantalum, wet, slug	High power transistor Hybrid IC (thick film)		Relays Servo
100	Heaters Thermostats Thermistors Temperature sensing	Tantalum, solid Mylar	High power diode	R.F. chokes and coils	Resolv Torque Blower
50	Variable Wirewound	Polystyrene Metal film	Zener diode Light emitting diode Monolithic IC, linear	Reactors and inductors Magnetic memory cores	Gyros, Counte Slip r
20	Carbon Film		Monolithic IC, digital Medium power transistor		Pulsed pend
10	Metal film Tin oxide	Glass Ceramic	Low power transistor Medium power diode		
5	Carbon composition		Low power diode		
2					
1					

TABLE 4.4.2.3-I

D Ratios for High Reliability Parts and Components*

vironment - equipment laboratory operation
clic rate - 6 cycles (or less) per 24 hours
me on - sufficient for temperature stabilization
rating - 50 percent or greater on devices in columns 1, 2, and 3

Semiconductors and Microelectronic Devices 3	Transformers and Inductors 4	Electromechanical and Rotating Devices 5	Electrical 6	
				2000
	Transformers			1000
brid IC (thin film)		Switches		500
gh power transistor brid IC (thick film)		Relays Servo motors		200
gh power diode	R.F. chokes and coils	Resolvers Torquer motors Blower motors	Lamps, incandescent Lamps, electrolumines Fuses	100
ner diode ght emitting diode nolithic IC, linear	Reactors and inductors Magnetic memory cores	Gyros, integrating Counters Slip rings	Lamps, annunciator	50
nolithic IC, digital dium power transistor		Pulsed integrating pendulum	Couplings** Connectors** Connector pins**	20
w power transistor dium power diode				10
w power diode				5
				2
				1

**Per connection

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Limitations of Table 4.4.2.3-I are many, of which a few are:

1. The ratio $K_{C/D}$ can be assumed to be approximately equal to $K_{C/S}$ because no significant statistical difference has been found between λ_S and λ_D.

2. The cyclic rate will affect the ratios and this chart is for a slow cyclic rate of not more than 6 times per day and in which temperature stabilization occurs after each turn-on and turn-off.

3. The transient suppression protection provided is consistent with good design practices.

4. That only higher quality grades of parts are represented, such as TX, ER, or Class A and B for microelectronics.

4.5 Failure Modes and Mechanisms

A list of 29 failure modes and mechanisms which have been identified as occurring during power on-off cycling is provided in Table 4.5-I. These failures occurred on parts which were assembled into systems and are the same types which are expected to be observed in the future. In many cases, the malfunctions can be tied back to improper process control during manufacturing, a situation which may never be completely corrected. Even though electronic parts are subjected to screening and burn-in, followed by several functional tests at the assembly and system level, a small quantity of potentially defective items get into operational equipments. Power on-off cycling is one forcing mechanism which can cause those parts to fail in a catastrophic mode. As can be observed from the table, failure analysis of the part malfunction is still not a requirement on all major programs.

It is interesting to note that 90 percent of the failures listed in Table 4.5-I are opens. The reason for this high percentage can undoubtedly be attributed to expansion and contraction effects which take place when devices are energized and de-energized. Improper welds, defective solder joints, nicked fine wire, and marginal structural assemblies can fail when subjected to this environment.

Open windings in fine wire transformers are a generic manufacturing problem. Failures are normally associated with stress relief loops, wire nicks, and soldering of lead wires to the windings. Although thermal cycling is often used as a screen to detect these kinds of defects, it is possible that power on-off cycling represents a better way to identify potential malfunctions of this type. The reason for this is that power cycling can induce local hot spot heating at the area where the defect exists. The failure will then become apparent after a period of expansion and contraction caused by the power cycling.

Code B failures were obtained from a controlled experiment in which a 4000 hour cycling test was conducted, with each cycle consisting of 25 minutes power on and 5 minutes power off. Transistor internal lead wire/bond failures are believed to be the same mechanism which is discussed in more detail by Reference 13. The cycling rate for the Code A and C equipment was that which was normally experienced during operational use.

Although Table 4.5-I does not contain any integrated circuit failures, power on-off cycling and resultant differential expansion and contraction can create malfunctions in these devices especially when a glassivation layer has been employed for passivation purposes. A detailed discussion of this situation can be found in Reference 14.

TABLE 4.5-I

System Failures Occurring During Power On-Off Cycling

System	Quantity	Part Type	Failure Mode
A	6	Transformer	Open
A	2	Transformer	Open
A	1	Transformer	Open
A	3	Switch	Open
A	1	Capacitor, Solid TA	Open
A	1	Capacitor	Open
B	1	Capacitor, Wet TA	Short
B	1	Capacitor	Open
A	1	Transistor	Open
A	1	Transistor	Open
B	1	Transistor	Open
B	1	Transistor	Short
C	1	Transistor, Power	Open
B	4	Diode	Open
B	1	Diode	Short
A	1	Lamp, Pilot	Open
A	1	Motor, Tach. Gen.	Open
A	1	Thermistor	Open
	29	Total	

System Code

A = Space Vehicle
B = Surface-to-Surface Missile
C = Satellite

TABLE 4.5-I

■ Failures Occurring During Power On-Off Cycling

Part Type	Failure Mode	Description
sformer	Open	Magnet Wire Fractured
sformer	Open	Internal Lead Wire Broken
sformer	Open	Nick In Stress Relief Loop
ch	Open	Defective Solder Joints and Connections
citor, Solid TA	Open	Defective Internal Weld
citor	Open	Defective Internal Solder Joint
citor, Wet TA	Short	Electrolyte Leak
citor	Open	Manufacturing Defect
sistor	Open	Metalization Defect
sistor	Open	Improper Bond of Collector Lead
sistor	Open	No Failure Analysis
sistor	Short	No Failure Analysis
sistor, Power	Open	Broken Internal Lead Wire
	Open	No Failure Analysis
	Short	No Failure Analysis
Pilot	Open	Broken Filament
, Tach. Gen.	Open	Improper Solder Connection
istor	Open	Wafer Fractured

e
urface Missile

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5.0 RELIABILITY MODELS

In recent years, an increasing number of electronic systems have been developed which are likely to be in a nonoperating or dormant mode for long periods, varying from a year to 5 or 10 years, before being used in their intended missions or replaced. Most of these systems must be capable of successful operation at any time with short notice. This greatly increases the importance of having a reliability mathematical model which accurately portrays the system reliability at any period during its life cycle.

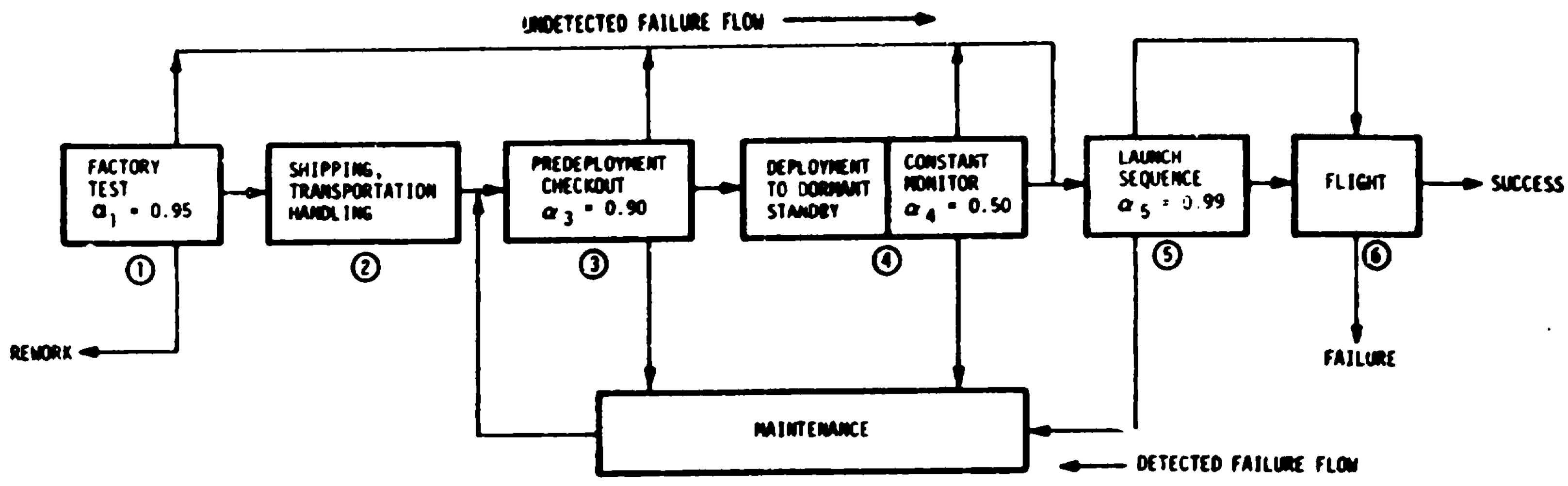
5.1 Service Life Model

The basic modeling techniques required for the prediction of system reliability in the dormant mode were established and validated in 1967 in Reference 1. These and subsequent techniques have resulted in a service life model that is a function of numerous system, subsystem, and device characteristics. The service life model evaluates system reliability in terms of the system's unique deployment schemes and design characteristics, which include the effects of:

1. Service life environmental (deployment) modes
2. Expected time in each mode
3. Power on-off cycling during test and checkout or operational usage
4. Failure detection capability of the system
5. Accumulation of operation, dormant, and cycling failures
6. Frequency of periodic test and checkout.

A simplified service life model is shown in Figure 5.1-1 for a missile system which is constantly monitored for failures after deployment. From the figure, note that the reliability of the missile after the dormant mode is a function of:

1. The undetected failures cumulated from prior modes
2. The dormancy failure rate and time in dormancy
3. The effectiveness, α_i, of the system test equipment.



1 UNDETECTED FAILURES THROUGH MODE 4: $F_4 = 0.05\ \lambda_1 t_{D_1} + 0.10\ [\lambda_2 t_{D_2} + \lambda_3 t_{D_3}] + 0.50\ \lambda_4 t_{D_4}$

SYSTEM RELIABILITY THROUGH MODE 4: $R_4 = e^{-F_4}$

2 FAILURES DETECTED DURING MODE 5: $F_5 = 0.99\ [F_4 + \lambda_5 t_{D_5}]$

PROBABILITY OF PASSING MODE 5: $R_5 = e^{-F_5}$

3 UNDETECTED FAILURES PASSED TO MODE 6: $F_6 = 1 - F_5 = 0.01\ [F_4 + \lambda_5 t_{D_5}]$

FLIGHT RELIABILITY: $R_6 = e^{-F_6}$

Figure 5.1-1 Service Life Model For Dormant Missile With Constant Monitor

If this missile system had been tested at periodic intervals during deployment rather than being constantly monitored, a fourth factor affecting the reliability of the missile would be the cumulative effects of power on-off cycling.

5.2 Storage and Dormancy Models

Strictly speaking, there are two primary types of submodels, each of which may or may not be present in a given service life model at the same time. These consist of a storage model and a dormancy model, which are broken down further in Table 5.2-I. The primary difference between the storage and dormancy models is in terminology. As the definition of storage implies, the storage model applies when an equipment is placed in storage or ''on-the-shelf'' for a certain time interval before either being deployed or used in its intended mission. While in storage, the equipment may or may not be periodically tested. The methods and failure rates used for determining equipment reliability are the same for the storage and dormancy models. Therefore, the paragraphs and examples describing the dormancy models will also apply to the equivalent storage models; i.e., periodic test and no test.

TABLE 5.2-I

Constituent Models of the Service Life Model

Service Life Model
1. Storage Model a. No test b. Periodic test
2. Dormancy Model a. No test b. Periodic test

The dormancy model is used in conjunction with two basic deployment survival techniques utilized for systems which are unlikely to be used in their intended mission for long periods of time after deployment. The first and simplest technique is the ''no test'' plan. Under this concept the system is deployed and never tested until used in its intended mission. For some of the less complex systems, this is the best method. However, as system complexity increases, other means must be found to assure that an acceptable reliability is maintained.

The second deployment survival technique is used for higher complexity systems which can experience considerable degradation over long periods of dormancy. In this technique, which is the periodic test concept, the deployed system is tested at periodic intervals, such as every 6 months, and any necessary repairs are made after each test.

5.3 Application of Reliability Models

To visualize the differences between the two basic deployment survival techniques, an example is provided which compares the two techniques by applying them to a tactical electronic system. The system is assumed to consist of high reliability parts and to be contained in a controlled environment during deployment. A parts list of the system with associated operating and dormancy failure rates is shown in Table 5.3-I.

In referring to Figure 5.1-1, Mode 4 of the service life model (deployment) is the only variation to be considered by this example. Therefore, the undetected failures through Mode 3 can be calculated to determine the system reliability, R_3, at the end of Mode 3 or the beginning of deployment:

$$F_3 = (1-\alpha_1)\lambda_E t_{E_1} + (1-\alpha_3)(\lambda_D t_{D_2} + \lambda_E t_{E_3})$$

where F_3 = expected failures through Mode 3

λ_E = 1,186,966.7 fits = System operating failure rate

t_{E_1} = 340 hours = Total operating time prior to shipment

λ_D = 14,876.25 fits = System dormancy (storage) failure rate

t_{D_2} = 720 hours = Total dormant (storage) time through Mode 2

t_{E_3} = 5 hours = Total operating time during predeployment checkout

α_1 = 0.95 = Test efficiency of factory test

α_3 = 0.90 = Test efficiency of predeployment checkout test

$$F_3 = 0.05(1,186,966.7\times10^{-9})(340) + 0.10\,[(14,876.25\times10^{-9})(720) + 1,186,966.7\times10^{-9}(5)]$$

$$F_3 = 0.0218$$

Thus $R_3 = e^{-0.0218} = 0.978$

Therefore, the system reliability at the beginning of deployment is 0.978.

5.3.1 No Test Deployment Concept

If the ''no test'' concept is chosen for the system, then the system will remain in a dormant, unenergized state throughout the deployment mode

Table 5.3-I

Part List and Failure Rates of Tactical System Used for Reliability Model Example

	Quantity Used (P)	Dormancy Failure Rates* (λ_D)	$P\lambda_D$	Operating Failure Rate* (λ_E)	$P\lambda_E$
Capacitor, Ceramic	662	0.7	453.40	8.0	5296.0
Glass	34	0.1	3.40	2.6	88.4
Plastic	11	1.5	16.50	4.4	48.4
Solid Tantalum	368	0.5	184.00	1.4	515.2
Variable Glass	5	5.0	25.00	15.0	75.0
Resistor, Carbon Composition	5	0.07	0.35	5.0	25.0
Metal Film	1,841	0.1	184.10	0.2	368.2
Power Wirewound	837	0.5	418.50	75.0	62775.0
Precision Wirewound	427	1.0	427.00	68.0	29036.0
Transistor, Low Power NPN	706	1.0	706.00	104.0	73424.0
High Power NPN	112	7.0	784.00	432.0	48384.0
Low Power PNP	127	1.5	190.50	124.0	15748.0
High Power PNP	82	10.0	820.00	766.0	62812.0
Diode, Low Power	1,462	0.3	438.60	22.6	33041.0
Medium Power	259	1.0	259.00	63.0	16317.0
High Power	5	3.0	15.00	94.0	470.0
Low Power Zener	161	0.7	112.70	118.0	18998.0
Integrated Circuit, Digital	1,926	2.0	3852.00	160.0	308160.0
Integrated Circuit, Linear	468	7.0	3276.00	480.0	224640.0
Hybrid, Thin Film	81	20.0	1620.00	3000.0	2[illegible]000.0
Filter	18	4.4	79.20	108.5	1953.0
Coil	57	3.0	171.00	92.5	5272.5
Connector	415	2.0	830.00	88.0	36520.0
TOTALS	10,069		14,876.25		1,186,966.7

*Failure rates are in fits and are for a high reliability class of parts (ER, TX, or MIL-STD-883 Class B) of its service life. No system failures will be detected during this period, and the total undetected failures occurring during Mode 4 (deployment) of the system service life are found as follows:

$$F_{N4} = \lambda_4 t_4$$

where F_{N4} = Expected failures during Mode 4 under ''no test'' concept

λ_D = 14,876.25 fits = Dormant failure rate

t_4 = 1 to 5 years = Expected deployment time

The model may be solved for the total expected failures for various time durations, and by utilizing the exponental equation, system reliability can be calculated.

Figure 5.3.1-1 shows the system reliability degradation during the deployment mode under the ''no test'' concept. Note that the initial reliability is not 1.0, but 0.978 which is a result of the undetected failures through Mode 3. Therefore, at the end of five years the system reliability would be 0.51, which is not acceptable for most tactical systems.

5.3.2 Periodic Test Concept

In order to maintain a higher reliability throughout deployment, a periodic test strategy may be chosen. As previously mentioned, complex trade studies are involved in selecting the optimum checkout interval. However, it shall be assumed that the trade studies have already been performed, and a periodic test interval of one year selected.

An important consideration with the periodic test concept is the effects of power on-off cycling on the system reliability. If the system does not have adequate transient suppression circuitry, the power cycling may have a disastrous effect upon system reliability and availability. It shall be assumed that the system under consideration does have protection against transients.

For calculating the estimated number of failures that occur between periodic test (including the effects of cycling during the test), certain values relating to the test must be established. The interval between periodic tests will be one year. The total operating time during a periodic test is assumed to be 3.0 hours, which also is sufficient time for the internal temperature rise to stabilize at the maximum operating value. The model for calculating the estimated failures is based upon the models derived in section 1.1 of this report which incorporated the effects of on-off cycling. The model used is taken from Equation 1.1.2-8 with $r_S = 0$:

$$F_P = [(r_D + N_C K_{C/D}) \lambda_D + \lambda_E r_E] t_{D_4}$$

where F_P = Expected failures during one periodic test interval

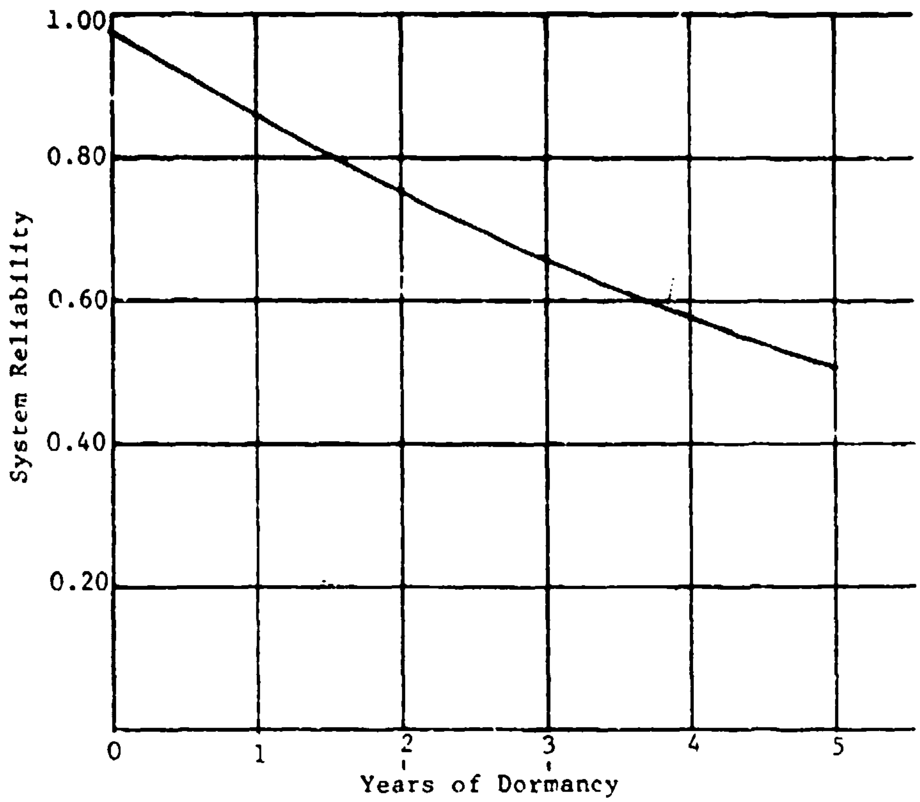


Figure 5.3.1-1 Reliability Degradation With No Test Deployment Concept

r_D = 0.99966 = Ratio of total dormant time to total periodic test interval time

N_C = 0.00023 = Ratio of total power cycles to total periodic test interval time (cycles per hour)

$K_{C/D}$ = 270 = Ratio of cyclic failure rate to dormancy failure rate (estimated for an average mix of high reliability parts)

λ_D = 14,876.25 fits = System dormant failure rate

λ_E = 1,136,966.7 fits = System energized failure rate

r_E = 0.00034 = Ratio of total operating time to total periodic test interval time

t_{D_4} = 8760 hours = Total periodic test interval time

The failure rate values are taken from Table 5.3-I. The ratios, r_D and r_E, are based upon the assumption of a one year periodic test interval (8760 hours) with a 3 hour operating time during test. A total of 2 power on-off cycles are assumed per test interval, from which N_C is obtained. The value of $K_{C/D}$ is assumed to have been determined for this system based upon such factors as high reliability parts, part mix, cyclic rate and duration, transient suppression capabilities, and energy level attained during cycling. Substituting these values into the model:

$$F_P = \{[(0.99966) + (0.00023)(270)]\ 14{,}876.25\times10^{-9} + (1{,}186{,}966.7\times10^{-9})(0.00034)\}\ 8760$$

$$F_P = 0.1419$$

By combining the value calculated for Fp with that of F_3 previously calculated and applying the sum to the exponental equation, the system reliability just prior to the first periodic test is obtained:

$$R = e^{-0.1637} = 0.849$$

Thus, by using the exponential equation, system reliability can be calculated at the time of test. Immediately after the periodic test, the reliability will be higher since detected failures will have been repaired. However, the reliability will not regain its former level at the previous periodic test because there are undetected failures remaining in the system. For comparative purposes, it shall be assumed that the value of α (efficiency of the test in detecting failures) can be either 0.50 or 0.95 depending upon the design and test equipment. The system reliability following test can be calculated in the following manner:

$$R = e^{-[(1-\alpha)(F_P) + F_3]}$$

For $\alpha = 0.50$:

$$R = e^{-[(1-0.50)\ (0.1419) + 0.0218]}$$

$$R = 0.911$$

For $\alpha = 0.95$:

$$R = e^{-[(1-0.95)\ (0.1419) + 0.0218]}$$

$$R = 0.972$$

Figure 5.3.2-1 shows the resulting reliability degradation over a five year period for both α values. As evidenced by the graphs, there is a considerable difference in reliability when the percentage of failures detectable is increased. Other than dormancy failure rate, the most significant contributors to achieving long term dormancy system reliability are the test efficiency and the frequency of periodic test.

It is interesting to note what effect power on-off cycling has on system reliability. If cycling were not taken into account, the model for the expected failures at the end of the first yearly periodic test would be:

$$F = (1-\alpha)\ [(\lambda_D\ t_{D_4}) + F_3]$$

where F_3 = Failures undetected prior to deployment

λ_D = Dormancy failure rate

t_{D_4} = Periodic test interval

α = Test efficiency

$$F = (.5)\ [(14{,}876.25\times10^{-9})\ (8760)] + 0.0218$$

$$F = 0.0870$$

Therefore,

$$R = e^{-0.0870}$$

$R = 0.917$ = Reliability without effects of cycling assuming 0.50 test efficiency

A comparison is shown in Table 5.3.2-I between the system reliability values calculated when the effects of on-off cycling are taken into account and when they are not considered. The values reflect an assumed test efficiency of 0.50 and a periodic test interval of one year. The differences are small, but become more significant when it is remembered that only 2 on-off cycles per year are being applied to the system.

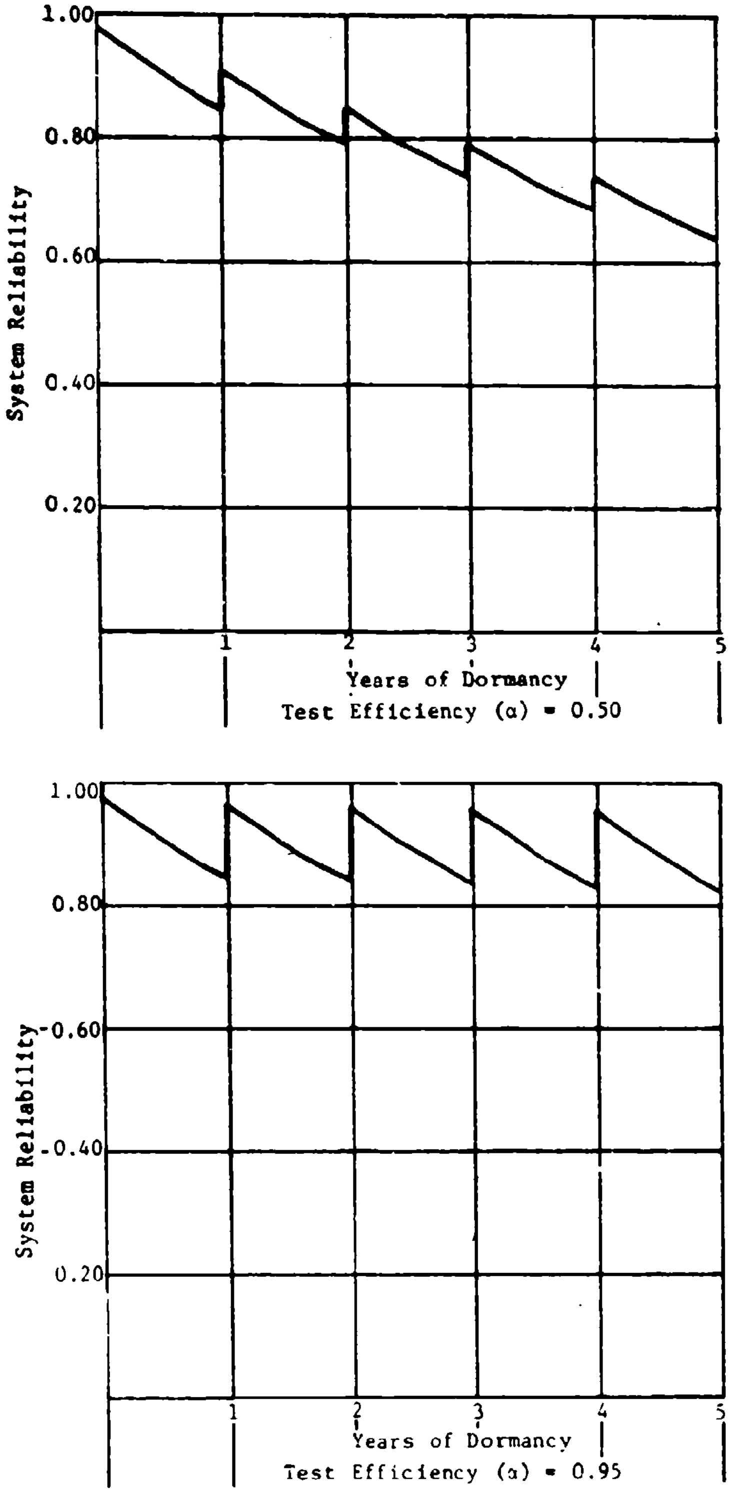


Figure 5.3.2-1 Reliability Degradation With Periodic Test Concept

TABLE 5.3.2-I

Comparison of Periodic Test Reliability Calculations
With and Without The Effects of On-Off Cycling

Time Interval (Years)	Reliability Calculations	
	With Cycling Effects	Without Cycling Effects
1	0.911	0.917
2	0.849	0.859
3	0.791	0.805
4	0.736	0.754
5	0.686	0.706
Note: 2 on-off cycles per year are assumed		

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Martin Marietta has thoroughly conducted and successfully concluded both RADC sponsored programs.

1 F30602-72-C-0243, "Dormancy Failure Rates of Electronic Equipment and Parts," and

2 F30602-72-C-0247, "Power On-Off Cycling Effects on Electronic Equipment Reliability,"

During the data collection and analysis phases of the above programs, definite interrelations between the storage, dormancy, power on-off cycling, and normally energized states were found, developed, and verified. These interrelationships have been incorporated into service life equations and models. Both apply to military electronic equipment and utilize failure contributions from the dormancy and power on-off cycling states in combination with those of the normally energized state.

The basic interrelationships, terms, and equations are given in Equations 1.1.2-1 through 1.1.2-9. The full spectrum of service life models has been carefully developed, explained, and illustrated in Section 5.0 RELIABILITY MODELS. The service life modeling techniques of Section 5.0 provide the means by which a system's reliability can be predicted or determined at any time during its service life cycle.

The study and investigation efforts of dormancy and power on-off cycling have been logically combined into this final technical report. This permits simultaneous retrieval of both sets of failure rates and interrelating factors from library sources. The logic and efficacy of a single report are also amplified by the fact that both studies have had the same ultimate goals:

1 The development and improvement in design, manufacturing, quality, and deployment techniques or conditions that promote attainment of maximum system reliability

2 The updating and upgrading of reliability predictions through improvements in military electronic system mathematical modeling methodology

3 The quantification of corresponding, viable, and authoritative failure rates and factors for dormancy and power on-off cycling from available field data.

6.1.1 Dormancy Program Conclusions

A statistical analysis of the dormant and storage data collected during this program indicates that there is no significant difference between failure rates for equivalent part types in the storage and dormant modes. As a result of this finding, the dormant and storage data have been combined for all analyses. Because of the unavailability of drift failure rate information, only catastrophic failure rates and factors have been developed.

6.1.1.1 Failure Rates, Factors, and Models

Dormancy data collected were primarily on three grades of electronic devices -- Military Standard, high reliability, and ultimate.

The data served to verify and strengthen the validity of the failure rates and factors originally developed in Reference 1. Many of the data gaps that previously existed have been filled, and changes in failure rates because of technological advances in design, manufacturing, and quality control are reflected. In almost all cases, the catastrophic failure rates have improved for individual electronic parts. These are summarized in Table 3.6.1-II for microelectronic devices, Table 3.6.2-I for resistors and capacitors, Table 3.6.3-I for semiconductors, and Table 3.6.4-I for low population devices.

Integrated circuit reliability has been expanded by categorizing the failure rates by the screening classes given in MIL-STD-883. Table 6.1.1-I shows the relative differences found to exist among the different classes for both digital and linear integrated circuits. Insufficient field data were available to make dormant failure rate estimates for MOS, MSI, and LSI devices.

Analysis of the data shows that, on the average, dormant high reliability part failure rates are between 3 and 7 times better than the Military Standard grade. The ultimate grade part appears to be about 50 times better than the Military Standard grade; however, data are still insufficient to draw good or prove definite conclusions on this grade.

TABLE 6.1.1-I

Failure Rate Factors for Digital and Linear Integrated Circuits by Classes A, B, and C of MIL-STD-883

Integrated Circuit Type	Reliability Class	Relative Failure Rate Factors
Digital	Class A	1*
	Class B	2*
	Class C	5*
Linear	Class A	1**
	Class B	3.5**
	Class C	10**

* Normalized to Class A, Digital

** Normalized to Class A, Linear

Based upon data from five systems with similar functions but with different vintages of designs and high reliability parts, dormant reliability growth trends have been determined. The growth trends indicate a steady improvement in average catastrophic dormant failure rates from 1964 to 1969. However, the rate of improvement has leveled off somewhat after 1967 and appears to be asymptotically approaching a level failure rate much more slowly after 1969. This failure rate improvement is primarily due to improved manufacturing control and more effective parts screening and burn-in as shown in Table 3.7.1.4-I and Figure 3.7.1.4-1.

Parametric drift information was sought on dormant devices, but has been found to be sparse. In general, however, parametric drift tests conducted on stored semiconductors have shown drift to be negligible on devices investigated. Positive drift trends have been observed on certain metal film and wirewound resistors. Even this drift rate does not indicate these types of resistors can be expected to go outside of end of life tolerances over a 10 year period. Insufficient drift data exist for other devices.

Because of the limited temperature and humidity ranges observed on the dormancy data, no pronounced differences in dormant catastrophic failure rates can be identified for temperature or humidity changes. Data from high temperature storage tests on microelectronic devices have been analyzed in a further attempt to correlate dormant failure rates with temperature. In general, the dormant failure rates increase with temperature, but the lack of more than two high temperature data points prevented the establishment of an Arrhenius curve and associated acceleration factors.

Quantification of relative environmental location factors for electronic systems has been accomplished for four dormant environments: satellite, in container in a controlled environment, not in container in a controlled environment, and submarine. The factors are listed in Tables 3.5.2-I and II.

The service life model previously mentioned has been developed to reflect the entire life cycle of a system from factory to replacement or use in its mission. The model enables the system reliability to be calculated at any given time throughout this cycle. Many of our strategic missile systems, both in the field today and under development, have a planned life cycle of approximately 10 years and must be capable of successful operation at any instant during this period. Thus, the importance of having a reliability mathematical model which accurately portrays the system reliability prior to deployment becomes paramount. The addition of power on-off cycling effects to this model increases the accuracy even more and is discussed in paragraph 6.1.2.1.

6.1.1.2 Dormancy Failure Modes and Mechanisms

Preliminary indications from failure mode data collected on approximately 100 electronic parts are that open and short failures occur with about equal frequency in the dormant state. However, a closer look at the data reveals that about 60 percent of the shorts experienced are due to contaminated integrated circuits. Without this failure mode, the opens are clearly in the majority.

The most prevalent type of open failures are lifted bonds on transistors and integrated circuits and electrolysis of Nichrome metal film resistors with entrapped humidity.

The shorted failure modes are primarily due to contaminated IC's, dielectric breakdown in ceramic capacitors, and electrolyte leakage in wet tantalum capacitors. Although examples of "purple plague" were not revealed, other types of intermetallic problems are still present. This is evidenced by failures of this type from two sources.

A major contributor to failures which occur during dormancy is out-of-control manufacturing processes. Metal film resistors have exhibited two failure mechanisms attributable to manufacturing processes. One was the presence of sealed-in moisture which initiated an internal electrolysis process that created voids in the Nichrome film. The other failure mode is caused by the resistive Nichrome element flaking off because the ceramic base cores were insufficiently cleaned before film deposition.

The integrated circuit contamination failures are also attributable to manufacturing processes. Sources reported that loose conductive particles on the substrate surface caused shorts in the devices. These are particularly devious failures to validate because of the mobility of the particles. For example, assume a dormant system in an airborne environment experiences sufficient vibration to cause a conductive contaminant to short an integrated circuit; the module containing the IC is removed for repair and transported to the repair facility. During transit, however, should the conductive particle move to another location on the substrate, the module will test perfectly good. All evidence of failure has vanished. One way of controlling this type of failure mechanism is to perform a screening test which monitors the electrical parameters of the device during vibration testing. Another way of avoiding this problem is to eliminate the failure mode by design and use of devices which have a surface passivation layer which negates any possible intermittent shorts from any contaminants that may be present.

Since the observed failure modes and mechanisms for dormancy are the same as those for the energized state, it can be concluded that dormancy itself is not the causative factor. Rather device material properties or incipient defects are. Both types of these failure mechanisms can be correlated with dormant time as well as operating time. The rate at which failures occur in dormancy is lower because of zero or near zero electrical stresses applied.

6.1.2 Power On-Off Cycling Program Conclusions

The results of the data collection and analysis program indicate that power on-off cycling can have a definite adverse effect upon electronic equipment reliability. The degree to which reliability is affected depends upon several factors such as part quality, cyclic rate, temperature effects, environment, and transient suppression capabilities of the system.

These factors are not always independent of one another, but rather depend upon system design and duty cycle characteristics. Therefore, great caution and care must be exercised in construction of any power on-off cycling mathematical model and development of quantitative values for factors in the model.

This report is considered to be the initial step toward defining the terms and factors related to power cycling and developing the necessary mathematical models and quantitative factors required for reliability prediction purposes. It should be recognized that this is only a starting point with more and better power on-off cycling data required before a high degree of confidence can be obtained in the prediction methods and values. However, with the partial verification of the models and factors afforded by the on-off cycling data collected, it appears that there is a reasonable validity in the approach taken in this report.

6.1.2.1 Failure Rates, Factors, and Models

The service life model which has been developed reflects the effects of power on-off cycling on equipment reliability along with the other service life conditions usually experienced by equipments: storage, dormancy, and the fully energized state. The model adds a new dimension to trade-off studies involving periodic testing. Without the effects of cycling taken into account, reliability predictions can be overly optimistic. Of course the degree of optimism is dependent upon the cyclic rate and related cyclic characteristics. In addition, the service life model is a valuable tool for determining logistic requirements. More accurate failure data on specific part types and quantities can be obtained as a result of including cyclic failure rates.

Based upon the data collected, a power cycling failure rate model to estimate the cyclic failure rate(λ_c) has been developed and is given in Equations 4.3.1-1 and -2. The model identifies, defines, and correlates the factors exerting primary influences on cycling failures: part quality, cyclic rate, temperature effects, environment, and transient suppression characteristics of the equipment. Preliminary quantification of these factors has been accomplished and tables are given with values for the factors in paragraph 4.3.1.

The temperature factor exerts a major influence over the model because of the large percentage (about 90 percent) of observed part failures which appear to be related to expansion and contraction resulting from temperature change. These factors can range from 1 to greater than 200. Further quantification of this important factor should be obtained by properly designed experiments in which certain critical influence factors would be varied while others would be held constant.

In addition to the cyclic failure rate model, cyclic failure rates (Tables 4.4.2.1-I and 4.4.2.2-I) have been constructed. The former table is on microelectronic devices and the latter on high reliability parts. Both tables apply only to electronic systems in a laboratory environment, having a cyclic rate of 6 cycles or less per 24 hours, having the cycle on time one hour or longer, having the time between cycles one hour or longer, having an average part derating of 50 percent or greater, and having transient supression circuitry designed in the equipment.

The incidence of power on-off cycling has been correlated to other states such as dormancy and normally energized. This correlation is in the form of ratios of the cyclic failure rates to those of dormancy and energized. Table 4.4.2.3-I is the first such attempt at developing and ranking these factors. By the use of these factors, it is now possible to estimate how much more stressful the cyclic state is when compared to the dormant state for similar electronic devices in identical power on-off cycling conditions. Analysis of this data indicates that on the system level a single power on-off cycle is between 1 and 375 times more stressful or effective in causing failures than one hour of dormant time. This wide range demonstrates just how great an effect cycling can have on equipment reliability. In contrast to this, the ratio of energized to dormant failure rate was between 40 and 100, depending upon the part and component mix within the system.

Correlation of power on-off cycling failure incidence with environmental application or with equipment type was thwarted. This was due to the fact that almost all of the validated power turn-on and power turn-off failures came from missile electronic systems in a laboratory environment.

6.1.2.2 Failure Modes and Mechanisms

Available failure mode and mechanism data indicate an overwhelming tendency of power on-off cycling to induce failures in the open mode. Approximately 90 percent of the failures analyzed were opens. The reason for this high percentage can be attributed to expansion and contraction effects which take place when devices are energized and de-energized. Improper welds, defective solder joints, nicked fine wire, and marginal structural assemblies can fail when subjected to this environment. In many cases the malfunctions which occurred can be tied back to improper process control during manufacture, a situation which may never be completely corrected.

Power on-off cycling appears to be particularly effective in precipitating poor conductivity fault points in a system. This is illustrated by on-off cycling failures detected in transformers with opens, breaks, fractures or bad solder points; in switches with poor solder joints; in capacitors with bad internal welds and solder joints; and in a tachometer-generator with a poor solder connection. Although thermal cycling is often used as a screen to detect defects such as those described for transformers, it is possible that power cycling represents a better way to identify potential malfunctions of this type. The reason for this is that power cycling can induce local hot spot heating at the area where the defect exists. The failure will then become apparent after a period of expansion and contraction caused by the power cycling.

6.2 Recommendations

The following recommendations are submitted for consideration and possible implementation:

1 Government documents establishing and defining overall reliability program requirements should be updated and upgraded to include management and/or technical provisions that stipulate and implement reliability requirements in terms of operational service life, rather than just the energized (operating) state.

2 Government technical manuals, handbooks, and guidelines should be issued or revised to include the methods, data, and references on how to cohesively conduct and to systematically perform quantitative reliability analyses for the total service life of military equipment. Such analyses must be based on required operational capabilities over the anticipated service life. Degradation effects on electronic equipment in various activation states, such as shelf-life, transportation, handling, testing, dormancy, and power on-off cycling must be considered in addition to only those of the normally energized (active) state. For example, Figure 6.2-1 depicts a possible revision to Figure 1 of MIL-STD-721B. This Military Standard should be updated in the INACTIVE TIME area and added to in the TRANSITION TIME area.

3 Detailed Government procurement documents, specifications, and contracts should also be revised and written to include reliability requirements and studies based upon total service life considerations. The reliability studies, including mathematical models, trade-offs, parametric analyses, allocations, or predictions, should be directed with the intent to promote attainment of optimum system reliability consonant with minimum cost and time impacts. These studies are applicable to all phases of the Government procurement cycle; i.e., Concept Formulation, Advanced Development, Research and Development, Production, Deployment, and Operational.

MIL-STD-721B
(POSSIBLE REV.)

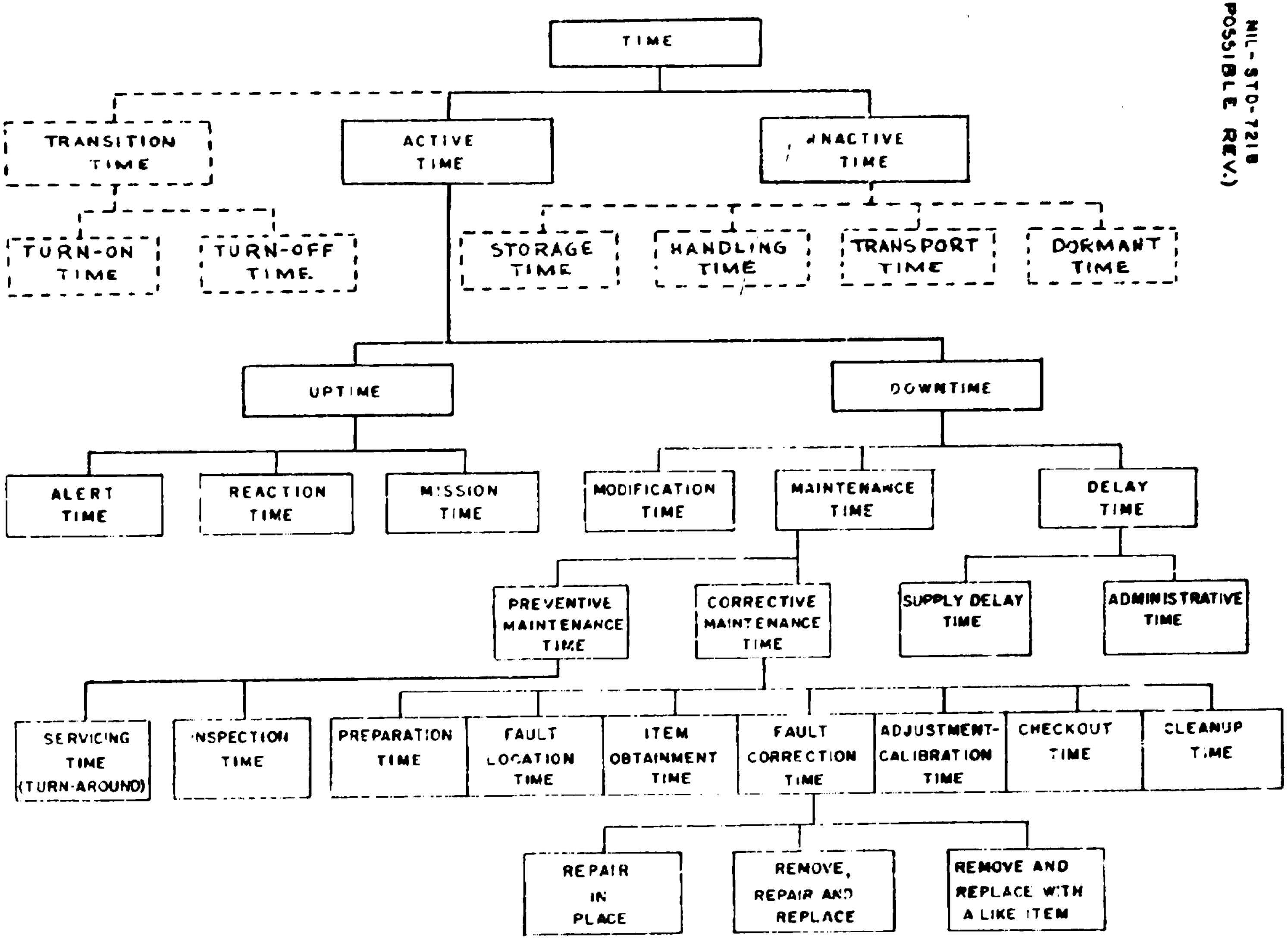


Figure 6.2-1 Possible Revision to Figure 1 of MILITARY STANDARD 721B

4 Consideration should be given to the feasibility of restructuring or of incorporating the means by which large quantities of dormant and power on-off cycling data can be collected through existing data collection systems. No such provisions now exist; nor are complete dormancy or power on-off cycling data on any current major military systems available from a single source.

5 In order to provide the huge quantities of dormancy or power on-off cycling data necessary, consideration should be given to selecting and marking a future major military electronic system for special data collection provisions on dormancy and power on-off cycling. These special provisions must include the necessary detailed and documented failure analysis provisions down to the part level to ascertain and validate the state in which failure occurred.

6 The possibility of establishing, at an existing facility, a central collection point for military electronic hardware failures (and their history) that are attributed to dormancy or power on-off cycling should be considered. At appropriate times, detailed failure analysis to pinpoint failure mode and failure mechanisms can then be readily accomplished to validate the failure and the state in which it occurred.

7 To establish power on-off cycling effects (factors, base failure rates, etc.) on specific electronic components, carefully constructed and designed experiments are needed. Careful contemplation should be made before attempting this because of hardware quantity and time constraints.

8 The efficacy of a low key effort to collect, when and as it occurs, power on-off cycling data of interest on military electronic equipment should be investigated. In the study just completed, a growing tendency has been noted. This tendency is a reluctance, on the part of major military weapon system contractors, to furnish uncontracted-for data free. This is due to material and manpower costs incurred by them in reconstructing or resorting past or present applicable data and not receiving monetary compensation for the added scope. This reluctance is further heightened by current cutbacks in military defense spending which directly results in purse-string tightening on the part of private contractors.

9 Should any of the recommendations of 4 through 8 be implemented, then additional study and investigation of any and all collected data should be undertaken. Although this technical report has provided new and updated dormancy failure rates and factors and provided an initial and unique approach to quantification of power on-off cycling effects, additional work is required to:

a Validate the preliminary dormancy failure rates arrived at by the ranking analysis method for both thick and thin film hybrid integrated circuits. This validation includes Class A, B, and C devices of MIL-STD-883.

b Establish and validate dormancy failure rates for other microelectronic devices such as MSI and LSI.

c Establish and/or validate dormancy failure rates for special electronic items such as MOS devices, field effect transistors, microwave diodes, or varactor and step recovery diodes.

d Validate dormancy failure rates for low population items.

e Develop additional values for the power on-off cycling to dormancy ratio ($K_{C/D}$) for use in the service life model.

f Validate the preliminary power on-off cycling failure rate (λ_C) model and provide further and better quantification of the base cycling failure rate (λ_{CB}) and contributing factors C_Q, C_{N_C}, C_T, and C_E.

g Provide more comprehensive rank ing tables for the base failure rate (λ_C).

h Provide a better delineation of the independent effects of temperature and humidity on dormant electronic devices.

i Provide a better correlation of power on-off cycling effects with environment and equipment type

j Provide a better delineation of environmental mode factors for dormancy and power on-off cycling especially for handling, transportation, or mobile states.

10 Power on-off cycling be investigated as an additional (and more effective) screening test for certain components-transformers, capacitors, thermistors, power transistors, inductors, switches, relays, motors, generators; i.e., those components or parts that utilize wire, wire connections, welds, solder joints, or filaments. It appears power on-off cycling is a more rigorous form of thermal cycling. It induces "local hot-spots" at potential conductivity faults resulting in wire, connection, or filament failure at that fault because of a correspondingly greater amount of expansion and contraction (work-hardening) induced.

11 The effect of power on-off cycling on poor solder joints or weld joints should be further investigated and developed because of a lack of low cost, reliable methods to test for or eliminate potential conductivity faults on the part, component, module, printed circuit board, chassis, subassembly, or assembly levels.

12 Update the data on the effects of burn-in on the dormant and operating reliabilities of electronic systems and expand the data to individual parts and components.

13 Extend dormancy work into the area of nonelectronics associated with electronic equipment. No such compendium of information now exists.

7.0 GLOSSARY

Activation Level - The level of electrical stress applied to an electronic system; power-off is zero activation level; dormancy is 10 percent or less of normal activation level; power-on is normal activation level.

Activation State - The state or mode in which an item is; these states include storage, dormant, power turn-on, normal operating (energized) and power turn-off for this study.

Alternative Hypothesis - The hypothesis which will be accepted if the null hypothesis is rejected.

Calendar Time - Total elapsed time.

Catastrophic Failure - A change in the characteristics of a part resulting in a complete lack of useful performance of the item.

Commercial Parts - See part class.

Cyclic Rate - The number of cycles that occur over a given time period.

Derating - The design practice of applying some fraction of the rated stress of a part in order to increase service life.

Dormant Mode - The state wherein a device is connected to a system in the normal operational configuration and experiences below normal or periodic electrical and environmental stresses for prolonged periods up to 5 years or more before being used in a mission.

Drift Failure - A change in a measurement above or below the individual parameter range requirements stipulated in the part specification.

Energized - The state of normal activation.

ER - Established reliability.

FET - Field effect transistor.

Fit - A failure per billion hours.

High Power Device - A device rated greater than 5 watts.

High Reliability Parts - See part class.

IC - Integrated Circuit.

IRIG - Inertial rate integrating gyro.

Infant Mortality - Part failures due to deficiencies in manufacturing processes which occur soon after stress is applied.

LED - Light emitting diode.

LSI - Large scale integration.

Low Power Device - A device rated less than or equal to 1 watt.

MOS - Metal oxide semiconductor.

MSFC - Marshall Space Flight Center

MSI - Medium scale integration.

Medium Power Device - A device rated greater than 1 watt but less than or equal to 5 watts.

MIL-STD - Military Standard.

Military Standard Parts - See part class.

Nonoperating Mode - Equipment in the storage and/or dormant mode.

Null Hypothesis - The hypothesis under test in a statistical test.

PIPA - Pulsed integrating pendulum accelerometer.

Part Class

Commercial - A part which receives limited testing by the vendor and is not subjected to screening.

Military Standard - Group A environmental proof tests, and Group B electrical tests.

High Reliability - Military standard tests plus: selected vendor serializing; 100 percent receiving inspection; 100 percent burn-in.

Ultimate Reliability - High reliability tests plus: 100 percent extended burn-in; parameter drift screening; stringent quality inspection.

Part Quality - See part class.

Population - The larger set of objects from which a sample is drawn.

Power On-Off Cycle - That state during which an electronic system goes from the zero or near zero (dormant) electrical activation level to its normal system activation level (turn on) plus that state during which it returns to zero or near zero (turn off) or vice versa.

Rank Ordering - Application of engineering judgment to produce a relative scale of reliability within a part class.

SCR - Silicon controlled rectifier.

SSI - Small scale integration.

Service Life - Useful life of an electronic system and measured in calendar hours or time.

Service Life Cycle - The individual mode or modes of service life such as depot storage and predeployment checkout.

Significance Level - Probability of accepting the alternative hypothesis when the null hypothesis is true.

Storage Mode - The state wherein a device is not connected to a system but is packaged for preservation and experiences somewhat benign environments.

TX - Tested extra.

Transient Suppression - The inclusion of electronic circuitry or special design characteristics to eliminate voltage spikes which could cause anomalous operation.

Ultimate Reliability Parts - See part class.

8.0 SYMBOLS

These symbols are used throughout the text of this report. In special instances where a specific symbol is used once and explained on the same page, it is not included in the following list.

α' = Significance level

α = System test efficiency, i.e., that fraction of failures which are detectable in a system.

C = Total number of cycles during the service life.

C_E = Environmental mode factor; this factor is an adjustment factor for the various environments in which power on-off cycling occurs.

C_{N_C} = Cycling rate factor; this factor is a function of the expected cycling rate (normally expressed as cycles per hour); the cycling rate can be estimated for a given system as

$$N_C = \frac{N}{t_{SL}}$$

that is, the total number of actual or anticipated power on-off cycles that will occur on that item during its entire service life expressed in hours. This factor represents all non-temperature related effects such as mechanical shock, wear, vibration, material fatigue, creep, or other cyclic induced stresses.

C_Q = Part quality (grade or class) factor; this factor is a function of the manufacturing process and subsequent controls imposed such as Group A and B electrical tests, special screens, or burn-in on individual parts and components. In addition C_Q is improved on equipment and systems which in turn, have assembly limited environmental tests and/or burn-in tests imposed.

C_T = Temperature effect factor; this is a complex factor comprised of several sub-factors which are dependent:

1 initial temperature state,

2 applied electrical energy versus part derating with resultant thermal stresses

3 thermal lags at turn-on and at turn-off,

4 temperature stabilization state (time to and time at),

5 residual temperature effects (a function of time between cycles),

6 environment.

C_{TS} = Transient suppression factor; this factor is a function of the degree to which transient suppression circuitry and design have been provided to eliminate or reduce damaging voltage or current transients at power turn-on or turn-off. These transients may either be line conducted or induced by internal or external sources.

$\sim$ = Cycle

e = 2.71828... = base of natural logarithms

ER = Established Reliability (as covered by Established Reliability specifications)

$fits$ = Failures per billion part-hours

F = Expected number of failures

$\tilde{F}$ = Statistic calculated for Brownlee's test

F_C = Expected number of failures during the power on-off cycling state within the service life of an electronic system.

F_D = Expected number of failures during the dormancy state within the service life of an electronic system.

F_E = Expected number of failures during the energized state within the service life of an electronic system.

F_i = Expected number of failures during the i'th state within the service life of an electronic system.

F_r = Rejection value for Brownlee's test.

$F_\rho(\gamma_1, \gamma_2)$ = The i'th percentage point of an F distribution with γ_1 and γ_2 degrees of freedom.

F_S = Expected number of failures during the storage state within the service life of an electronic system.

F_{SL} = Expected number of failures during the service life of an electronic system.

H_a = Alternative hypothesis

H_o = Null hypothesis

i = Index of summation, multiplication, etc.

$K_{C/D} = \frac{\lambda_C}{\lambda_D}$ = ratio of cyclic failure rate to dormancy failure rate (in hours of dormancy per cycle).

$K_{C/S} = \frac{\lambda_C}{\lambda_S}$ = ratio of cyclic failure rate to storage failure rate (in hours of storage per cycle).

$K_{E/S} = \frac{\lambda_E}{\lambda_S}$ = ratio of energized failure rate to storage failure rate (in hours of storage per energized hour).

λ = Constant failure rate, expressed as failures per unit of time, cycles, miles, etc.

λ_C = Cyclic failure rate

λ_D = Dormant failure rate

λ_E = Energized failure rate

λ_i = Failure rate of i'th population

$\hat{\lambda}_i$ = Estimate of λ_i

Log x = Logarithm of X

λ_S = Storage failure rate

λ_{SL} = Service life failure rate

N = Average number of cycles expected

$N_C = \frac{C}{t_{SL}}$ = Average cycling rate expected during the service life of an electronic system (in cycles per total unit time of service life).

n = The number of states, items, failure rates, etc., to be operated upon by Σ or π

ν_i = Number of failures observed from population i

P = Total quantity of parts

P_{SC} = Probability of success

P_{SL} = Probability of success during service life

R_C = Reliability of component

R_i = Quantitative system reliability at end of i'th period

$r_D = \frac{t_D}{t_{SL}}$ = Ratio of total dormant time to total service lifetime

$r_E = \frac{t_E}{t_{SL}}$ = Ratio of total energized time to total service lifetime

$r_S = \frac{t_S}{t_{SL}}$ = Ratio of total storage time to total service lifetime

R_{SL} = Reliability during service life

T_I = Initial temperature

T_S = Stabilized temperature

t = Total time

t_B = Time of burn-in (in hours)

t_D = Total dormant time in the service life of an electronic system

t_{D_i} = t_D for i'th period

t_E = Total energized time in the service life of an electronic system

t_{E_i} = t_E for i'th period

t_i = Number of part hours observed for population i

t_{m_1} = Time required to reach T_S

t_{m_2} = Time required to return to room ambient

t_S = Total storage time during the service life of an electronic system

t_{S_i} = t_S for i'th period

t_{SL} = Total elapsed time (calendar time) during the service life of an electronic system

$\therefore$ = Therefore

V = Voltage

$\bar{X}$ = Arithmetic average

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APPENDIX A

TESTING THE EQUALITY OF TWO LIFE DISTRIBUTIONS

It can be observed that ν_1 and t_1 are from population 1 and ν_2 and t_2 from population 2 where ν_i is the number of failures observed in t_i part-hours from the i'th population. The failure rate λ_i of the i'th population can then be estimated as $\hat{\lambda}_i = \nu_i/t_i$. A test of the null hypothesis H_o: $\lambda_1 = \lambda_2$ versus the alternative hypothesis H_a: $\lambda_1 \neq \lambda_2$ with significance level α' is desired.

The following procedure from Brownlee (Reference 15) accomplishes the desired test:

1. Choose notation such that $\dfrac{\nu_1}{t_1} > \dfrac{\nu_2}{t_2}$

2. Calculate the statistic $\tilde{F} = \left(\dfrac{\nu_1}{\nu_2+1}\right)\left(\dfrac{t_2}{t_1}\right)$

3. Determine the rejection value $\tilde{F}_r = F_{\alpha/2}(\gamma_1, \gamma_2)$ from a table of the "F distribution" for $\gamma_1 = 2(\nu_2+1)$ degrees of freedom and $\gamma_2 = 2\nu_1$ degrees of freedom.

4. If $\tilde{F} \geq \tilde{F}_r$, reject H_o and accept H_a declaring that populations 1 and 2 have different failure rates. If $\tilde{F} < \tilde{F}_r$, additional consideration is necessary before accepting H_o and stating that population 1 and population 2 are identical. If the difference between λ_1 and λ_2 is small, a large quantity of data will be needed for it to be detected. If the experimenter deems that sufficient data are present to detect any important difference in the two populations, then $\tilde{F} < \tilde{F}_r$ does imply that H_o should be accepted and the two populations can be declared identical.

Brownlee's test requires that an estimate of the failure ra : exists for both of the populations being compared. Thus, if no failures .ave been observed in either population, then Brownlee's test cannot be applied.

APPENDIX B

DATA COLLECTION

Data have been collected by Martin Marietta from approximately 50 contractors and government agencies and as a result of a comprehensive literature review.

I. Literature Review

More than 650 documents have been reviewed for information or data pertinent to dormancy and/or power on-off cycling. These documents were obtained from the Defense Documentation Center (DDC), RADC, GIDEP, FARADA, other government data sources and agencies, private contractors and vendors, research institutions, and the Martin Marietta Technical Information Center.

A primary source was the DDC from which two classified bibliographies were obtained consisting of abstracts and titles of documents related to dormancy and cycling. After reviewing these bibliographies, all appropriate documents were requested from DDC and reviewed in more detail. The most significant documents obtained from DDC and the other sources are listed in the bibliography of this report.

II. Data Source Contacts

Through initial literature and telephone surveys, those government agencies, military installations, private research institutions, and electronic manufacturing firms having data pertinent to dormancy and power on-off cycling were contacted.

A summary of those data sources contributing to these study programs is shown in Table B-I. The following paragraphs give a brief description of the type of data obtained from each source.

a. Autonetics
Anaheim, Calif.

Nonoperating data on Minuteman III were provided by Autonetics personnel. Since Minuteman III is powered up after site activation, only data generated before silo installation could be used.

b. Bell Telephone Laboratories, Inc.
Whippany, N. J.

A large amount of dormancy data was obtained from BTL on three sources: an Air Force missile guidance system, SPRINT/SPARTAN missile guidance sets, and components associated with the Bell System undersea cable repeaters.

TABLE B-I

Data Source Contacts

Autonetics
Anaheim, Calif.

Bell Telephone Laboratories, Inc.
Whippany, N. J.

Boeing Company
Seattle, Wash.

Cubic Corporation
San Diego, Calif.

Dale Electronics
Columbus, Neb.

Fairchild Semiconductor
Mountain View, Calif.

Film Capacitors, Inc.
Passaic, N. J.

General Dynamics
Pomona, Calif.

General Electric Company
Pittsfield, Mass.

General Electric Company
Syracuse, N. Y.

General Electric Company
Utica, N. Y.

George C. Marshall Space Flight Center
Huntsville, Ala.

Harris Semiconductor
Melbourne, Fla.

Hewlett-Packard
Palo Alto, Calif.

Honeywell, Inc.
Minneapolis, Minn.

Lockheed - Missile Systems Div.
Sunnyvale, Calif.

Lockheed - Satellite Systems Div.
Sunnyvale, Calif.

Manned Spacecraft Center
Houston, Texas

Martin Marietta, Denver Division
Denver, Colo.

Martin Marietta, Orlando Div.
Orlando, Fla.

Massachusetts Institute of Technology
Charles Stark Draper Laboratories
Cambridge, Mass.

McDonnell-Douglas Astronautics Co.
Huntington Beach, Calif.

Monsanto
Cupertino, Calif.

Motorola
Phoenix, Ariz.

National Semiconductor
Santa Clara, Calif.

TABLE B-I
(continued)

Naval Ammunition Depot (NAD)
Crane, Ind.

Naval Weapons Station
Fleet Missile Systems Analysis and Evaluation Group (FMSAEG)
FARADA Section
Corona, Calif.

Newark Air Force Station
Newark, Ohio

Ogden Air Material Area (OOAMA)
Hill Air Force Base, Utah

Perkin-Elmer
Danbury, Conn.

Philco Ford
Palo Alto, Calif.

RCA
Somerville, N. J.

Raytheon Company
Mountain View, Calif.

Raytheon Company
West Andover, Mass.

Reliability Analysis Center (RAC)
Griffiss Air Force Base, N. Y.

Rome Air Development Center (RADC)
Griffiss Air Force Base, N. Y.

Sandia Corporation
Albuquerque, N. M.

Signetics
Sunnyvale, Calif.

Siliconix
Santa Clara, Calif.

Singer-Kearfott, Inc.
Little Falls, N. J.

Strategic Air Command Headquarters
Offutt Air Force Base, Neb.

TRW Systems
Norton Air Force Base, Calif.

TRW Systems
Redondo Beach, Calif.

Texas Instruments Inc.
Dallas, Texas

U. S. Air Force Flight Test Center
Edwards Air Force Base, Calif.

U. S. Air Force Space and Missile Systems Organization (SAMSO)
Norton Air Force Base, Calif.

U. S. Army Electronics Command (USAECOM)
Fort Monmouth, N. J.

U. S. Navy Special Projects Office
Washington, D. C.

c. Boeing Company
Seattle, Washington

Data on parts parameter drift over long periods of time were obtained from Boeing.

d. Cubic Corporation
San Diego, Calif.

Data were received on digital integrated circuits used in vote counters manufactured by Cubic. These counters are in storage between elections, and therefore, are a good source of data.

e. Dale Electronics
Columbus, Neb.

High temperature storage data on resistors were provided by Dale.

f. Fairchild Semiconductor
Mountain View, Calif.

High temperature storage data on linear, digital, and MSI integrated circuits were obtained from Fairchild. On-off cycling data were also received.

g. Film Capacitors, Inc.
Passaic, N. J.

High temperature storage data on paper mylar capacitors were obtained from this source.

h. General Dynamics
Pomona, Calif.

A report containing testing and dormancy data on the REDEYE missile was provided by General Dynamics.

i. General Electric Company
Pittsfield, Mass.

A description of the operational profile and failure reporting techniques for the Polaris/Poseidon Fire Control systems was given by GE - Pittsfield personnel. Reports were also obtained relating to the Fire Control systems.

j. General Electric Company
Syracuse, N. Y.

A small amount of dormancy data on transistors was obtained from this source.

k. General Electric Company
Utica, N. Y.

A considerable amount of on-off cycling and dormancy data was obtained from GE - Utica on satellite equipment.

l. George C. Marshall Space Flight Center
Huntsville, Ala.

NASA data on aluminum wire fatigue problems during power cycling were obtained from this source.

m. Harris Semiconductor
Melbourne, Fla.

High temperature storage data were provided on digital, linear, and MSI integrated circuits.

n. Hewlett-Packard
Palo Alto, Calif.

High temperature storage data on LED's were obtained from Hewlett-Packard.

o. Honeywell, Inc.
Minneapolis, Minn.

Data generated at Honeywell on power on-off cycling tests on airborne equipment were provided.

p. Lockheed - Missile Systems Division
Sunnyvale, Calif.

Tab runs containing generation breakdowns of the Polaris and Poseidon missiles and failure data were obtained from Lockheed-MSD. Because of insufficient identification of part types in the generation breakdowns, absence of sufficient information in the failure tab runs, and lack of time periods in the dormant state for the missiles; it was determined that dormancy data could not be obtained on Polaris/Poseidon missiles within the time and manpower limitations of this contract.

q. Lockheed - Satellite Systems Division
Sunnyvale, Calif.

Dormancy data on satellites and dormancy failure mode information were obtained from Lockheed-SSD personnel.

r. Manned Spacecraft Center
Houston, Texas

NASA personnel provided failure summary reports on Apollo dormancy and on-off cycling failures.

s. Martin Marietta, Denver Division
Denver, Colorado

Dormancy data related to failure mechanisms, manufacturing processes and controls, and screening techniques were provided by the Denver Division of Martin Marietta.

t. Martin Marietta, Orlando Division
Orlando, Florida

Dormancy and power cycling data on the SPRINT system as well as power cycling data on the Pershing system were provided by the Orlando Division of Martin Marietta.

u. Massachusetts Institute of Technology
Charles Stark Draper Laboratories
Cambridge, Mass.

A large and well documented quantity of on-off cycling and dormancy data on the Apollo electronics was provided by the MIT personnel.

v. McDonnell-Douglas Astronautics Company
Huntington Beach, Calif.

Data on the SPARTAN missile were obtained from McDonnell-Douglas through BTL.

w. Monsanto
Cupertino, Calif.

Life test data on LED's and information on LED failure mechanisms were obtained from Monsanto.

x. Motorola
Phoenix, Arizona

On-off cycling and high temperature storage data were provided on various types of integrated circuits, transistors, and diodes by Motorola personnel.

y. National Semiconductor
Santa Clara, Calif.

High temperature storage data and on-off cycling data on integrated circuits were obtained from National Semiconductor.

z. Naval Ammunition Depot (NAD)
Crane, Indiana

A considerable amount of dormancy data related to the Poseidon Fire Control system was obtained from NAD, Crane including failure evaluation reports, part lists, and nonoperating times.

aa. Naval Weapons Station
Fleet Missile Systems Analysis & Evaluation Group (FMSAEG)
FARADA Section
Corona, Calif.

Several reports concerned with on-off cycling and dormancy were received from FARADA. Dormancy data on the Terrier missile were also provided through FMSAEG.

bb. Newark Air Force Station
Newark, Ohio

A very useful tab run containing failure summaries of Minuteman II burn-in and zero time failures was loaned to Martin Marietta for use on the program.

cc. Ogden Air Material Area (OOAMA)
Hill Air Force Base, Utah

Tab runs containing Minuteman II and III failure data were obtained from OOAMA personnel.

dd. Perkin-Elmer
Danbury, Conn.

Dormancy data on electronic equipments were provided by the Perkin-Elmer personnel.

ee. Philco Ford
Palo Alto, Calif.

Dormant satellite data from several satellite systems were provided by Philco Ford.

ff. RCA
Somerville, N. J.

Data concerning power on-off cycling tests on transistors were obtained from RCA.

gg. Raytheon Company
Mountain View, Calif.

High temperature storage data on transistors, diodes, and integrated circuits were provided by the Semiconductor Division of Raytheon.

hh. Raytheon Company
West Andover, Mass.

Dormancy data on the Improved Hawk missile were obtained from the Raytheon personnel.

ii. Reliability Analysis Center (RAC)
Griffiss Air Force Base, N. Y.

Information concerning reports pertinent to dormancy and on-off cycling was obtained from RAC.

jj. Rome Air Development Center (RADC)
Griffiss Air Force Base, N. Y.

Reports and pertinent data related to dormancy and power cycling were provided by RADC. In addition, RADC-TR-67-307 (Reference 1) and the RADC Reliability Notebook (Reference 16) were used during the performance of the program effort and in compiling this final report.

kk. Sandia Corporation
Albuquerque, N. M.

Dormancy data on electronic parts were received from Sandia, but because of unforseen delays the data arrived too late to be analyzed or included in the report.

ll. Signetics
Sunnyvale, Calif.

A small amount of storage data was obtained on integrated circuits.

mm. Siliconix
Santa Clara, Calif.

A small amount of high temperature storage data was obtained on integrated circuits.

nn. Singer-Kearfott, Inc.
Little Falls, N. J.

Dormancy data on electronic equipment manufactured by Singer-Kearfott were used in this report. These data were obtained from a published report (Reference 17) of the company.

oo. Strategic Air Command Headquarters
Offutt Air Force Base, Neb.

Air Force personnel provided a description of the computerized tab runs used for recording Minuteman field failure data and discussed the major failure mechanisms observed after periods of dormancy.

pp. TRW Systems
Norton Air Force Base, Calif.

Dormancy data on the Minuteman II missile were obtained from TRW through SAMSO. TRW was very helpful and provided a magnetic tape and supplementary tab runs of dormancy data.

qq. TRW Systems
Redondo Beach, Calif.

TRW provided data generated on satellite systems. Several reports were also provided which were pertinent to dormancy.

rr. Texas Instruments Inc.
Dallas, Texas

Pertinent data on integrated circuits and LED's were provided by Texas Instruments.

ss. U. S. Air Force Flight Test Center
Edwards Air Force Base, Calif.

Data were provided which contained cycling information on the C-5A aircraft.

tt. U. S. Air Force
Space and Missile Systems Organization (SAMSO)
Norton Air Force Base, Calif.

SAMSO approved release of Minuteman II dormancy data and served as the pivotal point of release for the data which included failure events and dormancy times.

uu. U. S. Army Electronics Command (USAECOM)
Fort Monmouth, N. J.

Dormancy and on-off cycling data were obtained from special tests being conducted in Panama. Other potential sources of data were also given by USAECOM personnel.

vv. U. S. Navy, Special Projects Office
Washington, D. C.

Information related to the Polaris/Poseidon missiles and fire control systems was provided as well as specific contacts from which to obtain additional data.