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STORAGE RELIABILITY
OF
MISSILE MATERIEL PROGRAM

U.S. ARMY
MISSILE
RESEARCH
AND
DEVELOPMENT
COMMAND

STORAGE RELIABILITY ANALYSIS
SUMMARY REPORT
VOLUME I

ELECTRICAL & ELECTRONIC DEVICES

LC-78-2 JANUARY 1978

Redstone Arsenal, Alabama 35809

PRODUCT ASSURANCE DIRECTORATE

DMI FORM 1000, 1 APR 77

REPRODUCTION QUALITY NOTICE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(6) Storage Reliability of Missile Materiel Program

(9) Final rept. Jun 74-Jan 78

4. TITLE (and Subtitle)
Storage Reliability Analysis Summary Report. Volume I: Electrical and Electronic Devices.

5. TYPE OF REPORT & PERIOD COVERED
Final, June 1974 to Jan. 1978

6. PERFORMING ORG. REPORT NUMBER
LC-78-2, Volume I

7. AUTHOR(s)
(10) Dennis F. Malik

8. CONTRACT OR GRANT NUMBER(s)
(15) DAAH01-74-C-0853

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Raytheon Company, Equipment Division
3322 S. Memorial Parkway
Huntsville, Alabama 35801

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Headquarters, U. S. Army Missile R&D Command, ATTN: DRDMI-QS, Redstone Arsenal, Alabama 35809

12. REPORT DATE
(11) January 1978

13. NUMBER OF PAGES
328

(12) 334 p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
(14) LC-78-2-VOL-1

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Unlimited

for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Reliability, Storage, Missile Materiel, Failure Rates, Failure Mechanisms, Operation, Electrical Devices, Electronic Devices, Integrated Circuits, Microelectronics, Semiconductors, Transistors, Diodes, Resistors, Capacitors, Inductive Devices, Transformers

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes analyses on the non-operating reliability of missile electrical and electronic devices. The analyses are part of a research program being conducted by the U. S. Army Missile R&D Command, Redstone Arsenal, Alabama. The objective of the program is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. Included are analyses of Integrated Circuits, Semiconductors, Vacuum Tubes, Resistors, Capacitors, Inductive Devices, Crystals, Batteries

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

391 619

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. Key Words (continued)

Coils, Filters, Chokes, Inductors, Vacuum Tubes, Printed Wiring Boards, Connectors, Connections, Crystals.

20. Abstract (continued)

connections, connectors and printed wiring boards. This report updates and replaces report LC-76-2 dated May 1976.

(2)

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STORAGE RELIABILITY ANALYSIS
SUMMARY REPORT
VOLUME I
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LC-78-2 JANUARY 1978

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HEADQUARTERS
U. S. ARMY MISSILE RESEARCH & DEVELOPMENT COMMAND
REDSTONE ARSENAL, ALABAMA

IN COMPLIANCE WITH
CONTRACT NO. DAAK40-74-C-0853
DATED 4 JUNE 1974
DATA ITEM SEQUENCE NO. 3

RAYTHEON COMPANY
EQUIPMENT DIVISION

LIFE CYCLE ANALYSIS DEPARTMENT
HUNTSVILLE, ALABAMA

ABSTRACT

This report summarizes analyses on the non-operating reliability of missile materiel. Long term non-operating data has been analyzed together with accelerated storage life test data. Reliability prediction models have been developed for various classes of devices.

This report is a result of a program whose objective is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. The analysis results will be used by U. S. Army personnel and contractors in evaluating current missile programs and in the design of future missile systems.

The storage reliability research program consists of a country wide data survey and collection effort, accelerated testing, special test programs and development of a non-operating reliability data bank at the U. S. Army Missile Research & Development Command, Redstone Arsenal, Alabama. The Army plans a continuing effort to maintain the data bank and analysis reports.

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1.0 INTRODUCTION

1.1 Missile Reliability Considerations

Materiel in the Army inventory must withstand long periods of storage and "launch ready" non-activated or dormant time as well as perform operationally in severe launch and flight environments. In addition to the stress of temperature soaks and aging, they must often endure the abuse of frequent transportation and handling and the climatic extremes of the forward area battlefield environment.

Missiles spend the majority of the time in this non-operating environment. In newer missile systems, complexity is increasing significantly, longer service lives are being required, and periodic maintenance and checkouts are being reduced. The combination of these factors places great importance on selecting missile materiels which are capable of performing reliably in each of the environments.

The inclusion of storage reliability requirements in the initial system specifications has also placed an importance on maintaining non-operating reliability prediction data for evaluating the design and mechanization of new systems.

1.2 Storage Reliability Research Program

An extensive effort is being conducted by the U. S. Army Missile Research & Development Command to provide detailed analyses of missile materiel and to generate reliability prediction data. A missile material reliability parts count prediction handbook, LC-78-1, has been developed and provides the current prediction data resulting from this effort.

This report is an update to report LC-76-2 dated May, 1976. It provides a summary of the analyses performed under the storage reliability research program and background information for the predictions in LC-78-1. Included are summaries of real time and test data, failure modes and mechanisms, and conclusions and recommendations resulting from analysis of the data. These recommendations include special design, packaging and product assurance data and information on specific part types and part construction.

For a number of the part types, detailed analysis reports are also available. These reports present details on part construction, failure modes and mechanisms, parameter drift and aging trends, applications, and other considerations for the selection of materiel and reliability prediction of missile systems.

The U. S. Army Missile Research & Development Command also maintains a Storage Reliability Data Bank. This data bank consists of a computerized data base with generic part storage reliability data and a storage reliability report library containing available research and test reports of non-operating reliability research efforts.

For the operational data contained in this report, the user should refer to the following sources: MIL-HDBK-217B, Military Standardization Handbook, Reliability Prediction of Electronic Equipment; Reliability Analysis Center (RAC) Microcircuit Failure Rates; RADC-TR-69-458, Revision to the Nonelectronic Reliability Handbook; and the Government-Industry Data Exchange Program (GIDEP) Summaries of Failure Rate Data.

1.3 Missile Environments

A missile system may be subjected to various modes of transportation and handling, temperature soaks, climatic extremes, and activated test time and "launch ready" time in addition to a controlled storage environment. Some studies have been performed on missile systems to measure these environments. A summary of several studies is presented in Report BR-7811, "The Environmental Conditions Experienced by Rockets and Missiles in Storage, Transit and Operations" prepared by the Raytheon Company, dated December 1973.

In this report, skin temperatures of missiles in containers were recorded in dump (or open) storage at a maximum of 165°F (74°C) and a minimum of -44°F (-42°C). In non-earth covered bunkers temperatures have been measured at a maximum of 116°F (47°C) to a minimum of -31°F (-35°C). In earth covered bunkers, temperatures have been measured at a maximum of 103°F (39°C) to a minimum of 23°F (-5°C).

Acceleration extremes during transportation have been measured for track, rail, aircraft and ship transportation. Up to 7 G's at 300 hertz have been measured on trucks; 1 G at 300 hertz by rail; 7 G's at 1100 hertz on aircraft; and 1 G at 70 hertz on shipboard.

Maximum shock stresses for truck transportation have been measured at 10 G's and by rail at 300 G's.

Although field data does not record these levels, where available, the type and approximate character of storage and transportation are identified and used to classify the devices.

1.4 System Level Analysis

The primary effort in the Storage Reliability Research Program is on analysis of the non-operating characteristics of parts. In the data collection effort, however, some data has been made available on system characteristics.

This data indicates that a reliability prediction for the system based on part level data will not accurately project maintenance actions if the missile is checked and maintained periodically. Factors contributing to this disparity include test equipment reliability, design problems, and general handling problems. In many cases, these problems are assigned to the system and not reflected in the part level analysis.

In general, a factor of 2 should be multiplied by the device failure rate to obtain the maintenance rate. Three system examples are described below:

1.4.1 System A

For system A, a check of 874 missiles in the field indicates 142 failed missiles. These failed missiles were taken to a maintenance facility. At the maintenance facility, no fault could be found in 51 of the missiles. Two missiles faults were corrected by adjustments. This left 89 failures which could be attributed to part failure. The parts were failure analyzed and the analysis indicated 19 failures to be a result of electrical overstress. These failures were designated design problems.

Therefore only 70 (49%) of the original 142 failures were designated as non-operating part failures.

1.4.2 System B

For system B, 26 missile failures were analyzed. Of these no fault was found in 2 missiles; adjustments were required for 2; external electrical overstress or handling damage was found in 10; a circuit design problem was assigned to 1, and component failures were assigned to 11.

1.4.3 Gyro Assemblies

An analysis of gyro assembly returns indicated that two thirds of the returns were attributed to design defects, mishandling, conditions outside design requirements, and to erroneous attribution of system problems.

Therefore, only 33 percent of the returns were designated as non-operating part failures.

1.5 Limitations of Reliability Prediction

Practical limitations are placed in any reliability analysis effort in gathering and analyzing data. Field data is generated at various levels of detail and reported in varying manners. Often data on environments, applications, part classes and part construction are not available. Even more often, failure analyses are non-existant. Data on low use devices and new technology devices is also difficult to obtain. Finally in the storage environment, the very low occurrence of failures in many devices requires extensive storage time to generate any meaningful statistics.

These difficulties lead to prediction of conservative or pessimistic failure rates. The user may review the existing data in the backup analyses reports in any case where design or program decision is necessary.

1.6 Life Cycle Reliability Prediction Modeling

Developing missile reliability predictions requires several tasks. The first tasks include defining the system, its mission, environments and life cycle operation or deployment scenario.

The system and mission definitions provide the basis for constructing reliability success models. The modeling can incorporate reliability block diagrams, truth tables and logic diagrams. Descriptions of these methods are not included here but can be studied in detail in MIL-HDBK-217B or other texts listed in the bibliography.

After the reliability success modeling is completed, reliability life cycle prediction modeling for each block or unit in the success model is performed based on the definitions of the system environment and deployment scenario. This reliability life cycle modeling is based on a "wooden round" concept in order to assess the missile's capability of performing in a no-maintenance environment. The general equation for this modeling is:

$$R_{LC} = R_{T/H} \times R_{STOR} \times R_{TEST} \times R_{LR/D} \times R_{LR/O} \times R_L \times R_F$$

where:

R_{LC} is the unit's life cycle reliability

$R_{T/H}$ is the unit's reliability during handling and transportation

R_{STOR} is the reliability during storage

R_{TEST} is the unit's reliability during check out and test

$R_{LR/D}$ is the unit's reliability during dormant launch ready time

$R_{LR/O}$ is the unit's reliability during operational (>10% electronic stress) launch ready time

R_L is the unit's reliability during powered launch and flight

R_F is the unit's reliability during unpowered flight

The extent of the data to date does not provide a capability of separately estimating the reliability of transportation and storage for missile materiel. Also data has indicated no difference between dormant (>0 and <10% electrical stress) and non-operating time. Therefore, the general equation can be simplified as follows:

$$R_{LC}(t) = R_{NO}(t_{NO}) \times R_O(t_O) \times R_L(t_L) \times R_F(T_F)$$

where: R_{NO} is the unit's reliability during transportation and handling, storage and dormant time (non-operating time)

t_{NO} is the sum of all non-operating and dormant time

R_O is the unit's reliability during checkout, test or system exercise during which components have electrical power applied (operating).

t_O	is the sum of all operating time excluding launch and flight
R_L	is the unit's reliability during powered launch and flight (Propulsion System Active)
t_L	is the powered launch and flight time
R_F	is the unit's reliability during unpowered flight
t_F	is the unpowered flight time
t	is the sum of t_{NO}, t_O, t_L and t_F

The values R_{NO}, R_O, R_F are calculated using several methods. The primary method is to assume exponential distributions as follows:

$$\begin{aligned} R_{NO}(t_{NO}) &= e^{-\lambda_{NO} t_{NO}} \\ R_O(t_O) &= e^{-\lambda_O t_O} \\ R_L(t_L) &= e^{-\lambda_L t_L} \\ R_F(t_F) &= e^{-\lambda_F t_F} \end{aligned}$$

The failure rates λ_{NO}, λ_O, λ_L and λ_F are calculated from the models in the following sections. λ_{NO} is calculated from the non-operating failure rate models. The remaining failure rates are calculated from the operational failure rate models using the appropriate environmental adjustment factors. Each prediction model is based on part stress factors which may include part quality, complexity, construction, derating, and other characteristics of the device.

Other methods for calculating the reliability include wearout or aging reliability models and cyclic or one shot reliability models. For each of these cases, the device section will specify the method for calculating the reliability.

1.7 Reliability Predictions During Early Design

Frequently during early design phases, reliability predictions are required with an insufficient system definition to utilize the stress level failure rate models. Therefore, a "parts count" prediction technique has been prepared. It provides average base failure rates for various part types and provides K factors for various phases of the system deployment scenario to generate a first estimate of system reliability. This prediction is presented in Report LC-78-1.

1.8 Summary of Report Contents

The report is divided into five volumes which break out major component or part classifications: Volume I, Electrical and Electronic Devices; Volume II, Electromechanical Devices; Volume III, Hydraulic and Pneumatic Devices; Volume IV, Ordnance Devices; and Volume V, Optical and Electro Optical Devices. Table 1-1 provides a listing of the major part types included in each volume.

1.9 Extent of Volume I Update

This report updates report LC-76-2, Volume I dated May 1976. An additional 134 billion part hours and 613 failures have been analyzed. All non-operating failure rates have been updated. In most cases the extent of the failure rate update was minor. Table 1-2 summarizes the major changes that occurred in the analyses.

TABLE 1-1. REPORT CONTENTS

		Detailed Rept. Number & Date
Volume I	Electrical and Electronic Devices	
Section		
2.0	Microelectronic Devices	LC-78-IC1, 1/78
3.0	Discrete Semiconductor Devices	-
4.0	Electronic Vacuum Tubes	LC-78-VT1, 1/78
5.0	Resistors	-
6.0	Capacitors	-
7.0	Inductive Devices	-
8.0	Crystals	-
9.0	Miscellaneous Electrical Devices	-
10.0	Connectors and Connections	-
11.0	Printed Wiring Boards	-
Volume II	Electromechanical Devices	
Section		
2.0	Gyros	LC-78-EM1, 2/78
3.0	Accelerometers	LC-78-EM2, 2/78
4.0	Switches	LC-78-EM4, 2/78
5.0	Relays	LC-78-EM3, 2/78
6.0	Electromechanical Rotating Devices	-
7.0	Miscellaenous Electromechanical Devices	-
Volume III	Hydraulic and Pneumatic Devices	
Section		
2.0	Accumulators	LC-76-HP2, 5/76
3.0	Actuators	LC-76-HP3, 5/76
4.0	Batteries	LC-78-B1, 2/78
5.0	Bearings	-
6.0	Compressors	-
7.0	Cylinders	-
8.0	Filters	-
9.0	Fittings/Connections	-
10.0	Gaskets	-
11.0	O-Rings	-
12.0	Pistons	-
13.0	Pumps	LC-76-HP4, 5/76
14.0	Regulators	-
15.0	Reservoirs	-
16.0	Valves	LC-76-HP1, 5/76
Volume IV	Ordnance Devices	
Section		
2.0	Solid Propellant Motors	LC-76-OR1, 5/76
3.0	Igniters and Safe & Arm Devices	LC-76-OR2, 5/76
4.0	Solid Propellant Gas Generators	LC-76-OR3, 5/76
5.0	Misc. Ordnance Devices	-
Volume V	Optical and Electro Optical Devices	

TABLE 1-2. EXTENT OF VOLUME I UPDATE

		APPROX. NON-OPERATING DATA ADDED		MAJOR
SECTION	DEVICE	MILLION PART HOURS	FAILURES	CHANGES IN NON-OPERATING FAILURE RATES
2.0	Monolithic IC's	8000	126	Minor
	Hybrid IC's	1000	37	20% Increase
3.0	Transistors	8000	18	50% Decrease for FET and JAN Transistor
	Diodes	10000	8	Slight decrease in Zener & Microwave Diodes
4.0	Vacuum Tubes	225	371	Major update to include Hi Power Tubes
5.0	Resistors	50000	4	Decrease for Variable Resist
6.0	Capacitors	11000	8	Increase for Mica Capacitor Decrease for Paper & Plastic Solid Tantalum & Variable Capacitors
7.0	Inductors	5000	2	Decrease for Hi Rel Reactors
8.0	Crystals	57	2	Major decrease for Crystals
9.0	Batteries			Section moved to Volume III
9.0	Misc. Electrical Devices	37000	35	New Section
10.0	Connectors & Connections	2400	1	Decrease in Failure Rate
11.0	Printed Wiring Board	1800	1	Minor

2.0 Microelectronic Devices and Interconnections

Microelectronic devices have and continue to undergo a rapid development in design, materials, processes, screening and qualification procedures. Data applicable to one device may be significantly different from another device performing a similar function. This is a result of materials, processes, etc., and is particularly significant in the hybrid area. Based on the failure mechanism analysis, a detailed categorization of these devices will be necessary to assess assurance procedures to improve the storage reliability.

2.1 Monolithic Microelectronic Storage Reliability Analysis

Monolithic refers to a one chip device. They can be of the bipolar or MOS (metal oxide semiconductor) variety. The term bipolar refers to the two polarities of carriers that exist in the device. Both holes and electrons are essential for operation. MOS devices are "unipolar" since only one type of a carrier is used. For P channel MOS, the carriers are "holes" while electrons are the carriers for n-channel MOS.

Another distinction arises from the differing location of active regions. Bipolar devices are "bulk" devices. The active region is the base, several microns beneath the surface between the emmitter and the collector. MOS devices are "surface effect" devices. Their active region consists of a channel that is induced at the silicon/silicon-dioxide interface.

Because of the difference in construction and operation between bipolar and MOS devices, they are treated separately in this analysis.

Microelectronic device reliability depends primarily upon construction; process control, screening, qualification; and use characteristics. A review of the literature was performed to identify those characteristics which are listed in Table 2.1-1.

For convenience, device construction was broken into seven major areas: Bulk materiel and diffusion, oxide; metallization; glassivation; die bonding; chip connections; and packaging characteristics. Each of these areas identified in Figure 2.1-1 were

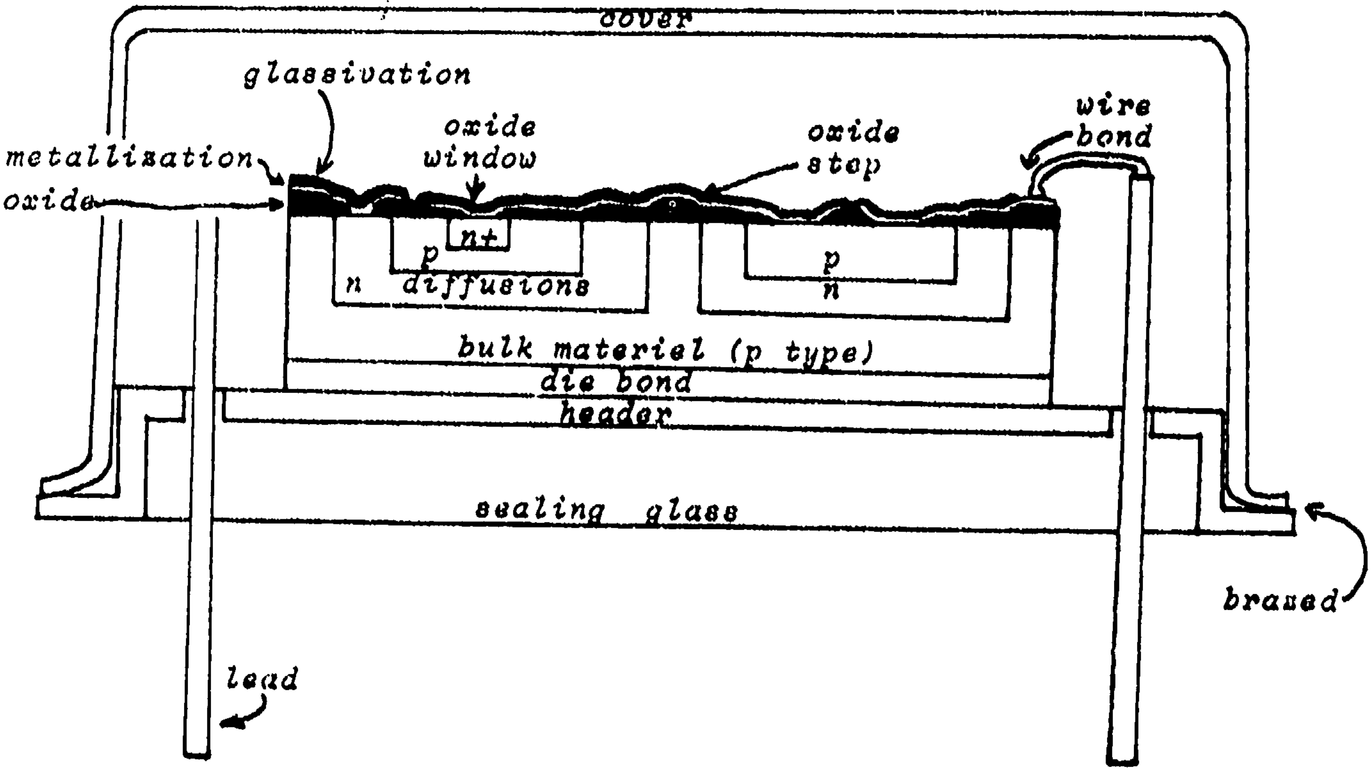


FIGURE 2.1-1. TYPICAL PLANAR MICROELECTRONIC DEVICE CROSS SECTION

analyzed for failure mechanisms which would be applicable in a missile's use environment from acceptance into the inventory to firing.

TABLE 2.1-1. DEVICE CLASSIFICATION

CONSTRUCTION

- Die Properties
- Oxide
- Metallization
- Glassivation
- Die Bond
- Chip Connection
- Package

DEVICE LEVEL PRODUCT ASSURANCE

- MIL-STD-883 Quality Level
- Screens
- Quality Conformance Inspection
- Process Controls

ASSEMBLY AND SYSTEM LEVEL PRODUCT ASSURANCE TESTS

COMPLEXITY

LOGIC TYPE

USE ENVIRONMENT

- Transportation and Handling
- Temperature
- Humidity
- Storage Container & Location
- Field Test Duration & Frequency
- Derating

2.1.1 Failure Mechanisms

The mechanisms of failures affecting semiconductors are generally the same regardless of the device type, however, the rate of occurrence varies between types. For this reason, the failure mechanism discussion applies to all of the monolithic device discussed in the succeeding sections.

The failure mechanisms contributing to microelectronic device failures appear to be identical whether the device is operational or in storage. The difference in the two environments is the frequency in which individual failure mechanisms occur. In general the mechanisms can be grouped into three categories:

1) Mechanisms for which failure occurrence is independent of the application environment.

2) Mechanisms for which failure occurrence is dependent on the application environment, and

3) Mechanisms for which the failure occurrence is time-related and environment dependent.

The mechanisms in group 1 are simply undetected defects which passed through the screens such as improper diffusions, oxide pinholes, etc. The rate of occurrence of these mechanisms would be the same, whether the device was applied in an operational or a storage environment. The only difference would be the time at which the mechanism was detected.

The mechanisms in group 2 are defects which do not fail the device immediately. For example, bond and metallization defects which progress to failure due to temperature or mechanical stress.

The third group of mechanisms are similar to group 2, except they are more time dependent. Examples are metal migration, intermetallic compound formations, corrosion, etc.

The mechanisms in groups 2 and 3 are dependent on environment and occur at different rates depending on whether the device is operational or dormant. In most cases, the storage environment is more benign than the operating environment.

In considering both operational and storage failure rates, the complexity of the device is important. The greater number of circuits on a given substrate area increases the temperature at which the devices are subjected and also requires greater process control in the production. The diffusions, metallization patterns and interconnections are very critical in a high density device.

In the operational environment, the rate of occurrence of particular failure mechanisms has differed between Bipolar Digital devices and Bipolar Linear and MOS devices. The major problem areas in digital devices have been contamination and oxide, wire bond and packaging defects. For Linear and MOS devices, contamination and metallization, die mount and oxide defects have been the

the major problem areas. Linear and MOS device failure rates are higher than digital devices because of the circuit sensitivity to surface, metallization and oxide defects.

Conversely, in the storage environment, analysis has indicated that the rate of occurrence of particular failure mechanisms is roughly the same between bipolar digital and linear devices. Insufficient data is available to make a storage assessment of MOS devices.

Table 2.1-2 lists each failure mechanism with its acceleration environment. These acceleration environments are the surrounding conditions which can speed the defect or degradation to the point of failure.

2.1.1.1 Bulk Materiel and Diffusion Characteristics

The primary reliability considerations in an operational environment associated with bulk phenomena are those which govern temperature of the device during operation. Devices are generally rated in terms of maximum allowable power dissipation. This power coupled with various thermal resistances and ambient temperature, determines the junction temperature of the device. Steps must be taken to maintain a controlled and uniform temperature since device degradation and failure modes, in most cases, are accelerated by increased temperature.

For most devices, the power requirements are not excessive and junction temperatures are controlled by using suitable heat-sink packages. For high-power devices, wafer design may include junction-temperature control considerations to prevent localized high currents and resultant "hot spot" formation.

Bulk defects account for only a minor portion of the operational and storage failures. Primary areas of concern include dislocations (crystal lattice anomalies); impurity diffusions and precipitations; resistivity gradients; and cracks in the bulk materiel. These defects usually result during crystal preparation and are accelerated by mechanical, nuclear and thermal stresses.

The failure modes resulting from bulk defects include deviations in voltage breakdown and other electrical characteristics;

secondary breakdown or uncontrolled p-n-p-n switching; or opens or shorts in the subsequent metallization.

Diffusion defects account for approximately 5 to 15% of operational and storage failures. Other than those diffusion problems associated with bulk materiel defects, the primary area of concern is the diffusion process itself. These include mask alignment; contamination; mask defects; cracks in the oxide layer; and improper doping profiles. Diffusions that are due to misalignment of masks reduce the base and emitter or base and collector junction spacings. Other faults include discontinuous isolation diffusions and odd shapes or edges of diffusions. Diffusion defects are primarily accelerated to failure by thermal cycling and high temperature. Principle failure modes resulting from diffusion defects include deviations in device characteristics and shorts between the emitter and base.

2.1.1.2 Oxide Considerations

Junction passivation of silicon devices is generally accomplished by using thermally grown silicon dioxide (SiO_2). Other devices use phosphorous pentoxide (P_2O_5) over the SiO_2 layer. Beam Lead Sealed Junction (BLSJ) devices utilize a layer of silicon nitride (Si_3N_4) glass deposited over the grown SiO_2. Both P_2O_5 and Si_3N_4 overcoatings have been found to improve the surface stability of bipolar devices. These materials act as gettering agents for sodium ions, thus making the contamination far less mobile. The stability of the structural and electrical properties of the oxide play an important role in determining the electrical characteristics and reliability of the passivated device.

Oxide defects are significant contributors to device failures. Approximately 5 to 50% of operational failures are attributed to these defects. Current data on non-operating failures indicates that approximately 5 to 35% of storage failures are attributable to oxide defects. Primary areas of concern are pinholes, cracks, thin oxide areas, and oxide contamination.

Pinholes can be caused by faulty oxide growth, a damaged mask, poor photo resist or an undercut by the etching process. They vary in depth and in the worst case, expose the silicon to the metallized interconnections. Where the pinhole or metallization does not extend completely to the surface of the silicon, a time-dependent migration or low voltage breakdown mechanism may occur. Where the oxide is overcoated with a second layer, the frequency of pinhole defects decreases.

Oxide cracks occur as a result of the mismatch in the thermal expansion rate of silicon and silicon dioxide. Diffusion of metal to the silicon is then possible. Thin oxide and other oxide difficiencies cause electrical breakdown in the surface passivation from the metal conductor to component areas in the silicon. All of these defects lead to increased current leakages or shorts from the metallization to diffusion areas or substrate.

Ionic impurities in the oxide may cause inversion layers, channeling, and other related phenomena creating lower threshold voltage. Ionic contamination is generally a significant contributor to total oxide charge. The ions are usually mobile and, by drifting under the influence of an electric field, can cause appreciable device parameter instability. Silicon nitride has been shown to be an effective barrier to sodium migration. In Beam Lead Sealed Junction (BLSJ) devices, the silicon nitride seals the devices from sodium and since the platinum silicide and titanium metals also offer very low mobility to the alkaline ions, the BLSJ is inert to sodium.

Inversion and channeling phenomenon occurs only with an electric field present. Bipolar linear and MOS devices are affected by this phenomenon greater than bipolar digital devices.

2.1.1.3 Metallization Considerations

A rather large number of metallization systems have been used on monolithic devices. The primary metals used have been aluminum, molybdenum-gold, and titanium-platinum-gold.

Failures related to metallization defects range from 7 to 26% in operational devices and current storage data indicates approximately 15% of the failures related to metallization.

Aluminum metallization defects result from manufacturing deficiencies and also from mechanisms inherent to the metal system.

Processing deficiencies which subsequently result in device failures include thin metal layers, poor metal-to-oxide adhesion due to oil or other impurities on the wafer, undercutting of Al during etching of the metallization pattern, bridging of Al between conductors due to unremoved photoresist, smears and scratches in conductor stripes, misalignment of masks, insufficient deposition at oxide steps, oxide steps too steep, incomplete removal of oxide, etc.

These defects are accelerated to failure primarily by thermal stresses and result in open and shorted conductors.

Mechanisms inherent to the aluminum metal system include electromigration formation, aluminum silicon eutectic, and intermetallic compound formations with gold.

Many of the failure mechanisms observed in molybdenum-gold metallization systems can be attributed to processing problems. These include failures due to unsatisfactory adhesion of molybdenum to the silicon dioxide and of the gold layer to the molybdenum layer. These can be attributed to contamination of the surface and oxidation of the molybdenum layer prior to deposition of the gold. Other processing problems include: molybdenum undercutting during etching; scratches which expose the molybdenum to oxidation and subsequent opens, and corrosion of molybdenum from impurities introduced in the processing.

Gold-silicon eutectics can occur if pinholes exist in the molybdenum layer.

Failure mechanism data on Platinum Silicide-Titanium-Platinum-Gold metallization systems is just becoming available. Improved or eliminated failure modes include wire bond defects, alkali ion contamination, metallization corrosion, and aluminum migration. Possible failure mechanisms identified for these devices are all due to processing deficiencies. They include pinholes in the silicon nitride; thin silicon nitride; shorted metallization; platinum migration into the silicon; gold or titanium migration resulting from thin platinum; and contamination.

2.1.1.4 Glassivation Considerations

Both silicon nitride and phosphosilicate glass overcoatings have been found to greatly enhance the reliability of bipolar digital devices. These glassivation materiels act as gettering agents for sodium ions and when deposited over the total surface, including the metallization, the materiel provides an excellent protection against metallization scratches and loose particle shorts.

Inversion and increased metal migration are two failure mechanisms that have been reported caused by glassivation. These new mechanisms are not fully understood but some causes have been postulated.

The induced inversion formation may result from some defects or contamination in the oxide layer which allow high fields to accumulate electronic charge over the underlying silicon. A poor interface between the oxide and glass then allows lateral charge movement along the interface. The lateral charge movement can induce inversion extensive enough to form a conducting channel which can cause device instability.

The increased metal migration is not as well understood but appears to be caused by the high pressure on the metal between the thermal and deposited glasses. Generally, the metal migration is associated with damage to the glass. Both aluminum and gold migration have occurred through the damaged glass to the adjacent conductor causing device failure.

A third possible failure mechanism has been discussed where condensation from any moisture in a package tends to concentrate on a crack in the glassivation, normally on the metal strips. This tends to increase the susceptibility for metal corrosion along the crack.

2.1.1.5 Die Bond Considerations

Die bonds provide mechanical support; in most cases, electrical contact; and also provide the principle path by which heat flows out of the silicon chip. Three techniques are in general use for attaching semiconductor devices to the package substrate: alloy mount, frit mount and epoxy mount.

Low strength chip-to-header bonds have been reported to result in approximately 2-7% of device failures, in both operational and storage environments.

The failure mechanisms include diffusion of the gold into the silicon producing void formations; brittle frit mounts resulting from impurities in the glass or improper firing cycles used for devitrification; mechanical stresses in epoxies where the temperature goes through the glass-transition temperature of the epoxy, and outgassing of organic materiel and separation of metal particles due to incomplete curing of the epoxy.

2.1.1.6 Chip Connection Considerations

Device connections are created by connecting wire leads to the device package; or through the use of beam lead or aluminum bump techniques. Wire bonding is accomplished primarily by thermocompression or by ultrasonic bonding techniques.

Wire bond defects are reported to account for 15 to 45% of all device failures in an operational environment. Storage or non-operating data currently indicates from 19 to 76% of all device failures are bond related.

The principle failure mechanisms are process deficiencies including underbonding, overbonding, misaligned bonds, contaminated bonding pads or wire, and wire nicks, cuts or abrasions.

Thermocompression bonding of aluminum wires has a history of cracks at the heel of the bond, which later failed under power cycling.

The gold wire bonding to aluminum metallization has been a major concern in microelectronic devices. Intermetallic compound formations between these two metals combined with the formation of voids in the aluminum from the Kirkendall effect create high resistance or weakened and brittle bonds. Formation of the compounds and voids is accelerated by thermal stresses. Design and processing criteria have been developed to minimize the occurrence of these formations. They include controlling the purity of the gold and providing thinner metallization at the bonding pad.

The aluminum wire bond to the gold header post has not been a significant contributor to device failures and is attributed to two factors: 1) the ratio of aluminum to gold is small, and 2) the bonds are not exposed to the same temperature as the gold wire to aluminum bonds on the chip during operation.

Failure mechanism data on beam lead sealed junction device bonding is limited. Processing deficiencies would be expected to be the primary problem, however, these are significantly reduced since the chip connection is made in the beam forming process which leaves only bonding of the beams to the header. All of the bonds of a single device are made simultaneously.

2.1.1.7 Package Considerations

Bipolar digital devices are packaged in a variety of materials and configurations. These materiels include: metal, ceramic, glass, metal ceramic, epoxy, phenolic and other plastics. Package configurations include cans, flatpacks, inline and dual inline.

Device failures attributed to package defects have been reported from 8 to 28% of operational failures. In many cases of failure reports, the resulting contamination and corrosion is reported and not the seal defect. Special test programs on devices have shown hermiticity problems to be substantial.

Failure mechanisms besides the seal leaks are fractured packages due to improper handling, loose solder balls formed in sealing the package which later short conductors, current leakage between leads from formation of lead from lead oxide in the glass, broken or burnt external leads and improper marking. All of these are process defects.

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
BULK DEFECTS				
Dislocation and Stacking Faults	Lattice strain due to steep concentration gradients finally released as dislocations.	Mechanical Stress Hi Temp	Degradation of junction characteristics.	Electrical Test
Impurity Diffusions and Precipatations	Diffusions along dislocations during epitaxial growth.	Hi Temp Power Burn-in Thermal Cycling	Low reverse breakdown voltage.	Electrical Test
Resistivity Gradiants	Large local stresses.	Mechanical Shock Vibration Nuetron Bombardment	Change in component values.	Electrical Test
Cracks in Bulk Materiel	Thermal shock during processing.	Mechanical Shock Thermal Cycling Hi Temp	Opens or Shorts in metal. Junction degradation.	Precap Visual Electrical Test

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
DIFFUSION DEFECTS				
Improper Diffusions	1) Faulty Mask Alignment 2) Dust or other Contaminants on mask 3) Defects in mask itself 4) Cracks in oxide	Hi Temp Thermal Cycling	Shorts Opens Changes in Device Characteristics.	Precap Visual Electrical Test
Improper Doping Profile	Process control problem.	Thermal Cycling Hi Temp. Storage	Unstable Components	Electrical Test
OXIDE DEFECTS				
Inversion Layer Phenomena	1) Thermal oxidation of Silicon producing n or p type surface. 2) Charged impurities.	Hi Temp. Power Burn-in Reverse Bias	Emitter to Collector Short Lower Threshold Voltage	Electrical Test
Pinhole	Faulty Oxide Growth due to: 1) Dust particles or other contaminants. 2) Minute mask flaws. 3) Etch undercut.	Hi Temp. Thermal Cycling Power Burn-in	Short	Electrical Test

TABLE 2.[illegible] MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
OXIDE DEFECTS -	CONTINUED			
Cracks	Mismatch in Thermal Expansion rate.	Hi. Temp.	Short	Electrical Test
Thin Oxide	Improper Process Control.	Hi. Temp.	Short	Electrical Test
METALLIZATION DEFECTS				
Surface Flaws	Scratched or smeared metallization during processing.	Thermal Cycling	Open Short	Precap Visual Electrical Test
Insufficient Coverage at Oxide step	1) Misalignment of masks. 2) Insufficient deposition at oxide steps. 3) Oxide step too steep. 4) Oversintering of metal to silicon. 5) Incomplete removal of oxide.	Hi. Temp. Thermal Cycling Power Burn-in	Open Hi Resistance Connections	Precap Visual Electrical Test
Under etched Metallization	Improper Etching.	Hi. Temp. Thermal Cycling Power Burn-in	Short	Precap Visual Electrical Test

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
METALLIZATION DEFECTS - CONTINUED				
Voids under Metallization	1) Overetching causing undercutting of metallization. 2) Kirkendall effect of disimilar alloys.	Hi. Temp. Thermal Cycling Mechanical Stress	Open	Precap Visual Electrical Test
Non-adhesion of Metallization	1) Contamination of surface. 2) Improper alloying temp. or time.	Hi. Temp. Thermal Cycling	Open	Precap Visual Electrical Test
Metal Migration (Hillocks, Voids, Whiskers, etc.)	Insufficient metal thickness, Scratches, grain size, etc.	Hi. Temp. & Current Density	Open Short Current Leakage	Precap Visual Electrical Test
Increased Resistance of Metallization	Thickness of oxide.	Hi. Temp.	Out of Tolerance	Electrical Test
GLASSIVATION DEFECTS				
Inversion Phenomenum	Poor Interface between oxide layer & glassivation layer.	Hi. Temp. & Reverse Bias	Out of Tolerance	Electrical Test

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
GLASSIVATION DEFECTS - CONTINUED				
Metal Migration	Damaged Glass - Pressure Between oxide & glassivation layers.	Hi. Temp. & Current Density	Open Short Current Leakage	Electrical Test
Oxide Cracks Corrosion	Thermal Shock During Processing.	Temp. Cycling	Open	Precap Visual Electrical Test
DIE BONDING DEFECTS				
Voids between header & die	Incomplete coverage of bonding materiel.	Hi. Temp. Vibration Shock	Open	Precap Visual Electrical Test
Cracked or lifted die to header bond.	1) Weak metal eutectic bond due to oxide on reverse side of silicon. 2) Glass frit facture in flexible package.	Acceleration Shock Vibration Hi. Temp.	Open	Precap Visual Electrical Test

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
DIE BONDING DEFECTS - CONTINUED				
Cracked Silicon Die	Strains during die attach.	Acceleration Shock Vibration	Open	Precap Visual Electrical Test
WIRE BONDING DEFECTS				
Separation of Bond	1) Underbonding. 2) Contamination of Bonding. 3) Cracks in bond due to overbonding.	Hi. Temp. Shock Vibration	Open	Precap Visual Electrical Test
Bond Shorts	1) Overbonding. 2) Insufficient bonding pad area or spacing. 3) Improper bond alignment.	Hi. Temp. Power Burn-in Vibration Shock Thermal Cycling	Short	Precap Visual Electrical Test
Broken wires & Reduced wire size.	1) Overbonding. 2) Nicks, cuts or abrasions in wire during processing.	Hi. Temp. Shock Vibration	Open	Precap Visual Electrical Test

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
WIRE BONDING DEFECTS - CONTINUED				
Wire Shorts.	Unremoved pigtails.	Hi. Temp. Shock Vibration	Short Intermittent Shorts	Precap Visual Electrical Test
Intermetallic Compound Formation	Various Time-Dependent Formations of a Chemical Compound at metal-metal contacts: 1) Purple Plague $AuAl_2$. 2) Black Plague Au-Si-Al. 3) White Plague - Aluminum Hydroxide. 4) Silver Plague - Tin Migration. 5) Red Plague - Copper Oxide on Silver Plate over Copper.	Hi. Temp. Power Burn-in Thermal Cycling	Open	Precap Visual Electrical Test
FINAL SEAL DEFECTS				
Poor Hermetic Seal	Fractured Glass or Imcomplete Weld, Braze, etc.	Thermal & Mechanical Stress	Corrosion Causing Opens, Shorts or Performance Degration.	Leak Tests

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
FINAL SEAL DEFECTS - CONTINUED				
Fractured Package	Improper Handling or Improper Seal Leak Test	Thermal & Mechanical Stress	Corrosion Causing Opens, Shorts or Performance Degration	Visual
Internal Wires Shorted to Conductive Lids or chip periphery.	Slack in leads.	Mechanical Stress Temp. Cycling	Short	Radiographic. Electrical Test
Current Leakage Between Leads	Low Resistance Leak due to Reduction of P_bO Glass to P_b.	Hi. Temp.	Current Leakage	Electrical Test
Broken or Bent External Leads	Improper Brazing or Handling	Hi. Temp. Mechanical Stress	Open	Visual Lead Fatigue Tests
Improper Marking	Process Control Problem		Not Operative	Electrical Tests

TABLE 2.1-2. MONOLITHIC DEVICE FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
CONTAMINATION				
Surface, Wire or Bond Corrosion	Corrosive Residue & Moisture such as: 1) Photo Resist 2) Chlorine in wire Lubricant 3) Etch pits in oxide, trapping sodium or other corrosive agents 4) Outgassing from organic materiels. 5) Weld glasses 6) Incorrect atmosphere sealed in package 7) Loss of package hermiticity	Hi. Temp. Storage	Open Short Degraded Operation	Electrical Tests
Conductive Particles in Package	1) Solder particles 2) Wire particles 3) Flaking metallization 4) Die particles 5) Die bond materiel particles	Vibration Shock Thermal Cycling	Short	Electrical Tests
Corrosion at Glass Ceramic Interface	Small lead materiel junction at interface exposed to environment after lead plating.	Hi. Temp. Storage	Open	Visual Electrical Tests

2.1.1.8 Device Level Product Assurance

The manufacturing controls and procurement methods for military equipment are normally determined by the criticality of the device in the system and the uniqueness of the device. Procurement specifications determine, to a significant degree, the reliability of the device in the field.

For standard devices in high volume production with established reliability, the parts may be procured according to the specifications in MIL-STD-883 and MIL-M-38510 or equivalent manufacturer specifications. The three quality levels defined in the military specifications are:

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.

A Class "D" level has also been defined in this report to identify the manufacturer's commercial quality level.

2.1.2 Monolithic Integrated Circuits Non-Operational Prediction Models

The general failure rate model for monolithic integrated circuits is:

$$\lambda_p = \Pi_L \Pi_Q (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

where: λ_p = device non-operating failure rate
Π_L = learning adjustment factor
Π_Q = quality adjustment factor
C_1 = temperature failure rate factor
C_2 = environment failure rate factor
Π_T = temperature adjustment factor
Π_E = environmental adjustment factor

The values for each of these parameters are given in Figures 2.1-2 and 2.1-3 for Monolithic Bipolar SSI/MSI Digital and Linear Devices. These devices have complexities less than 100 gates (approximately 400 transistors). The model in Figure 2.1-2 applies to devices containing aluminum metallization with aluminum interconnecting wires. The model in Figure 2.1-3 applies to devices containing aluminum metallization with gold interconnecting wires. A description of the parameters is given in the following sections.

No distinction is made in logic type or between complexity levels within the SSI/MSI complexity range.

At present insufficient data is available for devices with all gold systems including beam lead systems. Some data has shown that gold beam lead systems have a lower failure rate than the devices modeled. The model in Figure 2.1-2 can be used as a conservative prediction.

Data is insufficient at this time to develop models for Bipolar LSI, MOS and Memory devices.

2.1.2.1 Learning Adjustment Factor, Π_L

Π_L adjusts the model for production conditions and controls the conditions as defined in the figures for each device type.

2.1.2.2 Quality Adjustment Factor, Π_Q

Π_Q accounts for effects of different quality levels as defined in MIL-M-38510 and MIL-STD-883.

2.1.2.3 Temperature Adjustment Factor, Π_T

Π_T adjusts the model for temperature acceleration factors. Two models are applicable:

Π_{T1} is applicable to Bipolar Digital and Linear devices with aluminum metallization and aluminum interconnecting wires.

$$\Pi_{T1} = 0.1\, e^{x}$$

$$\text{where } x = -6608 \left(\frac{1}{T + 273} - \frac{1}{298} \right)$$

Π_{T2} is applicable to Bipolar Digital and Linear devices with aluminum metallization and gold interconnecting wires.

$$\Pi_{T2} = 0.1\, e^{x}$$

$$\text{where } x = -10502 \left(\frac{1}{T + 273} - \frac{1}{298} \right)$$

In Π_{T1} and Π_{T2} above, T is the ambient storage temperature (°C) and e is natural logarithm base, 2.718.

2.1.2.4 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in the Appendix.

2.1.2.5 Temperature Factor, C_1

C_1 is a constant and is the temperature component of the base failure rate. Values are given in the figures.

2.1.2.6 Mechanical Stress Factor, C_2

C_2 is a constant and is the mechanical stress component of the base failure rate. Values are given in the figures.

FIGURE 2.1-2

MONOLITHIC BIPOLAR SSI/MSI DEVICE NON-OPERATIONAL FAILURE RATE PREDICTION MODEL (FOR ALUMINUM METALLIZATION/ALUMINUM WIRE SYSTEM)

$$\lambda_p = \Pi_L \Pi_Q [\Pi_T C_1 + \Pi_E C_2] \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_Q (Quality Factor)

MIL-STD-883 Class	Π_Q
A	1
B	3.5
C	4.5
D	11.25

Π_T (Temperature Factor)

Temperature °C	Π_T
25	0.1
30	0.14
40	0.29
50	0.56
100	8.64
125	26.28
150	70.12
170	141.94

Π_E (Application Environment Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Naval, Unsheltered	6.0
Airborne, Uninhabited	5.0

C_1 (Temperature Base Failure Rate)

$C_1 = 0.00135$

C_2 (Mechanical Stress Base Failure Rate)

$C_2 = 0.00074$

FIGURE 2.1-3

MONOLITHIC BIPOLAR SSI/MSI DEVICE NON-OPERATIONAL FAILURE RATE PREDICTION MODEL (FOR ALUMINUM METALLIZATION/GOLD WIRE SYSTEM)

$$\lambda_p = \Pi_L \Pi_Q [\Pi_T C_1 + \Pi_E C_2] \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in the design or process
3) extended line interrupt or change in line personnel

Π_L = 1 otherwise

Π_Q Quality Factor)

MIL-STD-883 Class	Π_Q
A	1
B	3.5
C	4.5
D	135

Π_T (Temperature Factor)

Temperature °C	Π_T
25	0.1
30	0.18
40	0.54
50	1.53
100	119.53
125	700.71
150	3332.91
170	10223.86

Π_E Application Environment Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Naval, Unsheltered	6.0
Airborne, Uninhabited	5.0

C_1 (Temperature Base Failure Rate)

$\boxed{C_1 = 0.000034}$

T = Ambient Temperature °C

C_2 (Mechanical Stress Base Failure Rate)

$\boxed{C_2 = 0.00872}$

2.1.3 Non-operational Failure Rate Data

2.1.3.1 Bipolar Digital and Linear SSI/MSI Devices

The data collection effort for monolithic bipolar digital and linear devices has gathered approximately 20 billion hours of storage or non-operating field data with 270 device failures reported. In addition, 247 million plus hours of high temperature storage life data was collected with 711 device failures reported.

Ten data sources were used, two of which were reliability data banks, with the others representing specific programs. Field data included storage of missiles, warheads, satellite standby data and special parts testing programs.

Storage data collected is summarized in Tables 2.1-3 through 2.1-7. This data is organized in accordance to the metallization and interconnection systems.

A first characterization of the storage or non-operating data identified a definite correlation between the device failure rate and the device quality and temperature. No significant difference was measured between the non-operating data for digital and linear devices. Insufficient data was available to determine the effect of a learning factor or an application environment factor. The data on device complexity was analyzed but no significant differences were noted between the storage failure rate and the complexity of the device for SSI/MSI devices.

During the first characterization of the non-operating data, the failure experience indicated a sufficient difference between devices with aluminum metallization/aluminum wire systems and aluminum metallization/gold wire systems to require segregation of the data sets. This led to the segregation of data sets for other metallization/interconnection systems even though sufficient data was not available to completely characterize them.

The initial data characterization divided the data into several data sets with the prime category being metallization/interconnection systems, the first subcategory being quality level, and the second subcategory being ambient temperature.

Following this characterization, several other potential reliability factors were investigated. The results of the investigations indicated that no significant reliability difference was apparent in the data for storage duration, logic type, or package type. The data was insufficient to determine any factors for the die attach method or glassivation.

Failure mechanisms for 28 of the 372 storage life test failures of aluminum metallization/aluminum wire devices were reported. In the aluminum metallization/gold wire case, failure mechanisms for 155 of the 243 storage life test failures were reported. The distributions of failure mechanisms for both aluminum and gold wire systems are shown in Table 2.1-8.

Compared to the bipolar digital device data, considerably less data is available on the bipolar linear devices. A comparison of these two data sets indicated a close correlation. Insufficient data points were available on devices with aluminum metallization/gold wire systems to estimate a correlation.

A test of significance was performed to determine whether there was any significant difference in the linear and digital data points. The test indicated no significant difference and a decision was made to use the same model for the digital and linear data points.

Following the decision to use one prediction model, data on storage duration, device function, package type, die attach method and glassivation was analyzed for digital and linear devices combined to determine potential reliability problems. The results of the investigation indicated that no significant reliability difference was apparent for these factors.

Where identified, the real time data collected represented up to eight years storage durations. Tables 2.1-9 through 2.1-18 give the data by source and details are presented below.

2.1.3.1.1 Source A Data

The data under Source A includes over 9.5 billion storage hours for digital devices and 770 million storage hours for linear devices representing numerous missile and space programs. Twenty one failure were reported including lifted ball bonds due to intermetallics and Kirkendall voiding, metal corrosion, cracked dies, oxide defects and contamination. The data represents Class A, B, and C quality level devices. No details were available on storage environments or durations.

2.1.3.1.2 Source B Data

The storage data under Source B actually represents standby data in an orbiting satellite environment. No failures were indicated in 30 million hours. The devices were classified as approximately Class A devices since it was a space application.

2.1.3.1.3 Source D Data

The storage data under Source D represents lot samples placed in storage for three to four years. These devices have been tested approximately every 6 months and critical parameters have been recorded. The storage has been in an environmentally controlled facility. Evaluation of parameter changes indicated no significant trends. Out of 350 digital devices and 210 linear devices, no failures have been reported.

2.1.3.1.4 Source G Data

The storage data under Source G includes field data from four missile programs and one laboratory environment test. The date of the data sources range from 1967 thru 1970 and represents the only identifiable data on monolithic digital devices with aluminum metallization and gold wires (Al/Au) and on devices with gold metallization and gold wires (Au/Au).

Out of 2.7 billion part storage hours, 83 failures were reported for the Al/Au devices. No failure modes or mechanisms were provided other than the fact that the failures were catastrophic and not drift related. More recent data is available on Al/Au hybrid devices showing the same relatively high failure rate with wire bonds being the major problem (see Section 2.3).

Out of 290 million part storage hours, two failures were reported for Al/Al devices but no failure details were available.

No failures were reported in 18 million part storage hours for the Au/Au devices.

Storage durations for Al/Al devices indicated 2.4 years, and for Au/Au devices, 4 years. No storage durations were available on the Al/Au devices.

2.1.3.1.5 Source H Data

The storage data under Source H represents a special parts procurement and storage program. Parts are procured to the highest specification available from the vendor. The procuring agency then performs quality sampling on each lot including construction analysis and puts the device through an extensive rescreening approximating MIL-STD-883 Class A requirements. Under this procedure, 47,340 devices have been rejected and sent back to vendors out of 324,319 parts procured or an average of 14.6% rejects.

The devices passing the screens are placed in airtight storage tanks under controlled temperature and humidity conditions. The interior atmosphere of the tank contains nitrogen.

Samples from each lot are stored separately under identical conditions as control groups. The control groups are tested approximately three times a year. Parameter trends are evaluated from these tests. The main portion of each lot is not tested until required for program use or if control group parameters are drifting significantly. At this time, no significant drifts have been indicated.

Currently 118,467 monolithic digital & linear bipolar devices have been stored and tested. Ages of these devices range from one month to 8 years with an average of 1.5 years. 118 failures have been reported in these devices, however no failure analysis is available. One group of devices was removed from the analysis.

The data group removed was not considered representative of the general part class since all failures in the devices were related to a specific vendor's process. The group consisted of 12,774 devices stored for an average time of 1.3

years. Thirty one devices were reported failed after the storage period. Failure mechanisms were identical for all devices. The clearance of the interconnect wire to the chip was insufficient. After storage the wire contacted the chip periphery and shorted the device.

2.1.3.1.6 Source I Data

The storage data under Source I represents a special test program in 1974-75 to evaluate dormancy and cycling effects on microcircuits.

One thousand IC's were tested for 18 months with the following test profile:

Group	Profile
1	160 units, 2 days off, 1 hour on
2	160 units, 4 days off, 1 hour on
3	160 units, 7 days off, 1 hour on
4	160 units, 9 days off, 1 hour on
5	160 units, 12 days off, 1 hour on
6	200 units, control group, continuously operating

No failures were recorded in the SSI/MSI TTL devices tested.

2.1.3.1.7 Source J Data

The storage data under Source J represents field data from two warhead programs. Devices were procured under captive line provisions and are approximately equivalent to MIL-STD-883 Class A specifications. Of the 504 million part storage hours, no failures were reported. Storage durations ranged up to two years.

2.1.3.1.8 Source K Data

The storage data under Source K represents SSI RTL devices stored in an environmentally controlled area for eight years (1967 thru 1975). Three failures were recorded in the 10,027 devices all of which were analyzed as resulting from defects in the oxide.

Parameter analysis was performed on 2573 of these devices and compared with those measurements in 1967 to attempt to identify any trends over long term storage. The analysis concluded: "Parameter drift trends proved negligible in the resistance and transistor leakage characteristics. Transistor gain was the only parameter that exhibited a significant loss of performance during the eight years of storage, This is the one parameter that may have to be controlled to obtain a 10-20 year shelf life on these RTL devices."

Of the parts which showed degradation, the most significant performance losses were in those devices whose original performance was more than one standard deviation below the 1967 mean. The loss of performance was significant enough to class 24 parts as "incipient failures." There are parts whose performance has degraded near specification limits and could fall out of spec within the next few years of storage.

The shelf-life drift observed was attributed to one or a combination of following mechanisms:

1) Changes in the gold doping process, which is used to control the "parasitic transistor" condition, as well as to increase part switching speed.

2) Growth of a "parasitic transistor" condition due to migration of contaminants, or to changes in gold doping process.

2.1.3.1.9 Missile H Data

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions.

Four failures have been reported in 1.9 billion part storage hours. No analysis of the failures is available.

The devices include SSI and MSI TTL & SSI Linear devices and were procured to better than MIL-STD-883 Class C specifications. The user performed sample construction analysis on the devices and screened the parts to better than MIL-STD-883 Class B specifications.

2.1.3.1.10 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in the U. S. depots while the remainder were stored at various bases around the country.

Eight failures have been reported in 1.6 billion part storage hours. No analysis of the failures is available. The devices include SSI and MSI TTL and SSI linear devices which were procured to MIL-STD-883 Class B specifications.

2.1.3.2 MOS SSI/MSI Devices

The data collected on MOS SSI/MSI Devices did not include any field data but consisted of approximately 4 million hours of high temperature storage life data with 81 device failures reported.

Storage data collected is summarized in Table 2.1-19. Data is given by metallization/Interconnection Systems, quality level, storage temperature and complexity.

Failure modes or mechanisms for 35 of the storage life test failures were reported. These modes and mechanisms are listed in Table 2.1-20.

2.1.3.3 Bipolar & MOS LSI Devices

All data available on Bipolar and MOS LSI Devices was included in the memory section. This included complex (larger than dual 8-bit) static and dynamic shift registers. Smaller shift registers were included in the Digital SSI/MSI models.

TABLE 2.1-3. DIGITAL/LINEAR NON-OPERATING DATA FOR DEVICES WITH ALUMINUM METALLIZATION/ALUMINUM WIRE

QUALITY LEVEL	AMBIENT TEMPERATURE	FUNCTION	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS*
Class A	25-30°C	Digital	5,861.4	5	.85
		Linear	-	-	-
		Combined	5,861.4	5	.85
	125°C	Digital	.113	0	(<8850.)
		Linear	-	-	-
		Combined	.113	0	(<8850.)
	150°C	Digital	-	-	-
		Linear	.114	0	(<8772.)
		Combined	.114	0	(<8772.)
Class B	25-30°C	Digital	4,653.5	13	2.79
		Linear	2,018.8	9	4.46
		Combined	6,672.3	22	3.30
	125°C	Digital	.176	0	(<5682.)
		Linear	-	-	-
		Combined	.176	0	(<5682.)
	150°C	Digital	4.046	1	247.
		Linear	.139	0	(<7194.)
		Combined	4.185	1	239.
Class C	25-30°C	Digital	2,103.	8	3.8
		Linear	-	-	-
		Combined	2,103.	8	3.8
	125°C	Digital	.400	0	(<2500.)
		Linear	-	-	-
		Combined	.400	0	(<2500.)
	150°C	Digital	71.567	26	363.
		Linear	10.039	4	398.
		Combined	81.606	30	368.
	175°C	Digital	-	-	-
		Linear	6.289	8	1272.
		Combined	6.289	8	1272.
	180°C	Digital	.110	0	(<9091.)
		Linear	7.959	0	(<126.)
		Combined	8.069	0	(<124.)
	200°C	Digital	5.954	16	2687.
		Linear	3.034	1	330.
		Combined	8.988	17	1891
	250°C	Digital	3.100	23	7420.
		Linear	.338	3	8876.
		Combined	3.438	26	7564.
	300°C	Digital	3.656	59	16136.
		Linear	.292	3	10274.
		Combined	3.949	62	15701.
	350°C	Digital	2.152	148	68760.
		Linear	.069	4	58309.
		Combined	2.221	152	68438.

* Failures per billion hours.

TABLE 2.1-3.(Continued)

QUALITY LEVEL	AMBIENT TEMPERATURE	FUNCTION	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Class D	25-30°C	Digital	4.61	0	(<217.)
		Linear	-	-	-
		Combined	4.61	0	(<217.)
	100°C	Digital	-	-	-
		Linear	.01	0	(<100000.)
		Combined	.01	0	(<100000.)
	125°C	Digital	2.953	5	1693.
		Linear	-	-	-
		Combined	2.953	5	1693.
	150°C	Digital	53.702	46	857.
		Linear	15.496	19	1276.
		Combined	69.198	65	939.
	175°C	Digital	1.643	9	5479.
		Linear	-	-	-
		Combined	1.643	9	5479.
	180°C	Digital	.205	0	(<4878.)
		Linear	-	-	-
		Combined	.205	0	(<4878.)
	200°C	Digital	6.472	3	463.
		Linear	-	-	-
		Combined	6.472	3	463.
	300°C	Digital	.788	43	54358.
		Linear	.131	9	68702.
		Combined	.919	52	56574.
	350°C	Digital	-	-	-
		Linear	.041	29	710784.
		Combined	.041	29	710784.

TABLE 2.1-4. DIGITAL/LINEAR NON-OPERATING DATA FOR DEVICES WITH ALUMINUM METALLIZATION/GOLD WIRE

QUALITY LEVEL	AMBIENT TEMPERATURE	FUNCTION	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Class A	250°C	Digital	.01	0	(< 100000.)
		Linear	-	-	-
		Combined	.01	0	(< 100000.)
	300°C	Digital	.01	0	(< 100000.)
		Linear	-	-	-
		Combined	.01	0	(< 100000.)
	350°C	Digital	.01	0	(< 100000.)
		Linear	-	-	-
		Combined	.01	0	(< 100000.)
Class B	25-30°C	Digital	2604.11	77	30.
		Linear	114.0	6	53.
		Combined	2718.11	83	31.
Class C	150°C	Digital	15.848	50	3155.
		Linear	2.88	6	2083.
		Combined	18.728	56	2990.
	175°C	Digital	.282	0	(< 3546.)
		Linear	-	-	-
		Combined	.282	0	(< 3546.)
	200°C	Digital	.758	9	11873.
		Linear	-	-	-
		Combined	.758	9	11873.
	250°C	Digital	.315	13	41270.
		Linear	-	-	-
		Combined	.315	13	41270.
Class D	25-30°C	Digital	.268	0	(< 3731.)
		Linear	-	-	-
		Combined	.268	0	(< 3731.)
	125°C	Digital	.307	0	(< 3257.)
		Linear	-	-	-
		Combined	.307	0	(< 3257.)
	150°C	Digital	20.015	31	1549.
		Linear	.896	4	4463.
		Combined	20.911	35	1674.
	180°C	Digital	.086	7	81112.
		Linear	-	-	-
		Combined	.086	7	81112.
	200°C	Digital	.119	40	336417.
		Linear	-	-	-
		Combined	.119	40	336417.
	250°C	Digital	.068	99	1462000.
		Linear	-	-	-
		Combined	.068	99	1462000.

TABLE 2.1-5. DIGITAL NON-OPERATING DATA FOR DEVICES WITH GOLD METALLIZATION/GOLD WIRE

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Class B	25-30°C	.354	0	(<2825.)
Class C	25-30°C	8.689	0	(<115.)
Class D	25-30°C	8.689	0	(<115.)

TABLE 2.1-6. DIGITAL NON-OPERATING DATA FOR GOLD BEAM SEALED JUNCTION DEVICES

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Class B	150°C	.045	0	(<22200.)
Class D	150°C	2.41	0	(<415.)
	200°C	2.13	1	469.
	300°C	.062	0	(<16200.)

TABLE 2.1-7. SPECIAL STORAGE ENVIRONMENT DATA*

QUALITY LEVEL	AMBIENT TEMPERATURE	FUNCTION	STORAGE HRS. X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
B-A	22°C	Digital	1272.6	97	76.2
B-A	22°C	Linear	291.4	21	72.1

*Stored in Nitrogen Atmosphere.

TABLE 2.1-8. PRINCIPLE FAILURE MECHANISMS

Aluminum Metallization, Aluminum Wire, Gold Post

- Oxide Defects (31%)
- Wire Bond (19%)
- Diffusion Defects (16%)
- Surface Inversion (13%)
- Al-Au Post Bond (12&)
- Die Bond (3%)
- Lead Failures (6%)

Aluminum Metallization, Gold Wire, Gold Post

- Wire Bond (76%)
- Resistive Output (16%)
- Oxide Defects (4%)
- Die Bond (2%)
- Wire Shore (2%)
- Cracked Die (1%)

TABLE 2.1-9. SOURCE A DATA (FIELD & TEST)

FUNCTION OR LOGIC TYPE	COM- PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
DIG.	-	A	-	-	5328.2	5	0.9
DIG.	-	B	-	-	2269.7	5	2.2
DIG.	-	C	-	-	1952.9	8	4.1
LIN.	-	A	-	-	535.5	1	1.87
LIN.	-	B	-	-	235.5	2	8.49

TABLE 2.1-10. SOURCE B FIELD DATA

FUNCTION OR LOGIC TYPE	COM- PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
DIG.	-	A	-	7903	30.2	0	(<33.1)

TABLE 2.1-11. SOURCE D SPECIAL TEST DATA

FUNCTION OR LOGIC TYPE	COM- PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
TTL	SSI	B	Al/Al	30	.8	0	(<1250.)
TTL	SSI	B	Al/Al	20	.7	0	(<1429.)
TTL	SSI	B	Al/Al	30	.7	0	(<1429.)
TTL	SSI	B	Al/Al	10	.3	0	(<3333.)
TTL	SSI	B	Al/Al	10	.3	0	(<3333.)
TTL	SSI	B	Al/Al	10	.3	0	(<3333.)
TTL	SSI	B	Al/Al	10	.3	0	(<3333.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	30	.8	0	(<1250.)
TTL	SSI	B	Al/Al	20	.5	0	(<2000.)
TTL	SSI	B	Al/Al	20	.5	0	(<2000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	MSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	10	.2	0	(<5000.)
TTL	SSI	B	Al/Al	10	.2	0	(<5000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	30	.8	0	(<1250.)
TTL	SSI	B	Al/Al	20	.5	0	(<2000.)
TTL	SSI	B	Al/Al	20	.5	0	(<2000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
TTL	MSI	B	Al/Al	5	.1	0	(<10000.)
TTL	SSI	B	Al/Al	10	.2	0	(<5000.)
TTL	SSI	B	Al/Al	10	.2	0	(<5000.)
TTL	SSI	B	Al/Al	5	.1	0	(<10000.)
OP AMP	SSI	B	Al/Al	40	1.2	0	(<837.)
OP AMP	SSI	B	Al/Al	110	3.7	0	(<268.)
OP AMP	SSI	B	Al/Al	10	.4	0	(<2890.)
OP AMP	SSI	B	Al/Al	10	.2	0	(<4484.)
OP AMP	SSI	B	Al/Al	40	.9	0	(<1157.)

TABLE 2.1-12. SOURCE G FIELD DATA

FUNCTION OR LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
TTL	MSI	B	Al/Au	-	3.6	0	(<277.)
DTL	SSI	B	Al/Au	-	1240.	49	39.5
DTL	SSI	B	Al/Au	-	119.	5	42.0
TTL	SSI	D	Al/Au	-	.3	0	(<3333.)
CML	SSI	B	Al/Au	-	16.2	0	(<62.)
RTL	SSI	B	Al/Au	-	15.3	1	65.3
RTL	SSI	B	Al/Au	-	1210.	22	18.2
DTL	MSI	B	Al/Al	-	138.	2	14.5
DTL	SSI	C	Al/Al	-	150.	0	(<6.6)
RTL	SSI	D	Al/Al	216	4.6	0	(<217.)
RCTL	SSI	B	Au/Au	-	.4	0	(<2500.)
RCTL	SSI	C	Au/Au	55	1.9	0	(<518.)
RCTL	SSI	C	Au/Au	23	.8	0	(<1244.)
TCTL	SSI	C	Au/Au	10	.4	0	(<286.)
RCTL	SSI	C	Au/Au	41	1.4	0	(<694.)
RCTL	SSI	C	Au/Au	53	1.9	0	(<538.)
RCTL	SSI	C	Au/Au	3	.1	0	(<9524.)
RCTL	MSI	C	Au/Au	63	2.2	0	(<455.)
RCTL	SSI	D	Au/Au	55	1.9	0	(<518.)
RCTL	SSI	D	Au/Au	23	.8	0	(<1244.)
RCTL	SSI	D	Au/Au	41	1.4	0	(<699.)
RCTL	SSI	D	Au/Au	53	1.9	0	(<540.)
RCTL	SSI	D	Au/Au	10	.4	0	(<2857.)
RCTL	SSI	D	Au/Au	3	.1	0	(<9524.)
RCTL	MSI	D	Au/Au	63	2.2	0	(<455.)
AMP FAMILY	-	B	Al/Au	-	114.	6	52.6

TABLE 2.1-13. SOURCE H SPECIAL TEST DATA

FUNCTION OR LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
DTL	SSI	B-A*	Al/Al	517	5.9	0	(<169.5)
DTL	SSI	B-A*	Al/Al	22548	346.4	4	11.5
DTL	SSI	B-A*	Al/Al	17643	252.9	0	(<3.95)
DTL	SSI	B-A*	Al/Al	11852	170.1	25	147.0
DTL	SSI	B-A*	Al/Al	3015	29.7	4**	134.7
DTL	SSI	B-A*	Al/Al	2603	41.0	2**	48.8
DTL	SSI	B-A*	Al/Al	963	14.4	2**	13.9
DTL	SSI	B-A*	Al/Al	1597	16.7	1**	59.9
DTL	SSI	B-A*	Al/Al	4596	44.4	22**	495.5
DTL	MSI	B-A*	Al/Al	175	1.0	0	(<1000.)
DTL	MSI	B-A*	Al/Al	313	1.0	0	(<1000.)
DTL	MSI	B-A*	Al/Al	413	4.5	2	444.4
DTL	MSI	B-A*	Al/Al	138	1.9	0	(<526.3)
DTL	MSI	B-A*	Al/Au	63	0.2	30	150000.
RTL	SSI	B-A*	Al/Al	846	12.8	0	(<78.1)
RTL	SSI	B-A*	Al/Al	4454	52.3	0	(<19.1)
RTL	SSI	B-A*	Al/Al	1215	22.5	0	(<44.4)
RTL	SSI	B-A*	Al/Al	982	12.4	0	(<80.6)
RTL	SSI	B-A*	Al/Al	5172	90.1	0	(<11.1)
TTL	SSI	B-A*	Al/Al	4086	41.1	0	(<24.3)
TTL	SSI	B-A*	Al/Al	3835	42.7	0	(<23.4)
TTL	SSI	B-A*	Al/Al	329	4.7	0	(<212.8)
TTL	SSI	B-A*	Al/Al	714	7.0	2	285.7
TTL	SSI	B-A*	Al/Al	1998	12.6	0	(<79.4)
TTL	SSI	B-A*	Al/Al	2277	16.0	1	62.5
TTL	SSI	B-A*	Al/Al	560	3.6	0	(<277.8)
TTL	SSI	B-A*	Al/Al	1572	9.5	1	105.3
TTL	SSI	B-A*	Al/Al	39	.1	0	(<10000.)
TTL	SSI	B-A*	Al/Al	373	2.7	0	(<370.4)
TTL	SSI	B-A*	Al/Al	416	3.3	0	(<303.0)
TTL	SSI	B-A*	Al/Al	522	3.9	0	(<256.4)
TTL	SSI	B-A*	Al/Al	133	.6	0	(<1666.7)
TTL	SSI	B-A*	Al/Al	374	2.3	0	(<434.8)
TTL	MSI	B-A*	Al/Al	457	1.3	2	1538.5
TTL	MSI	B-A*	Al/Al	56	.4	0	(<2500.)
TTL-PROM	MSI	B-A*	Al/Al	37	.6	30	50000.
DC AMP	SSI	B-A*	Al/Al	2666	57.2	0	(<17.5)
OP AMP	SSI	B-A*	Al/Al	4948	80.3	9	112.1
DUAL COMP	SSI	B-A*	Al/Al	7521	88.9	1	11.2
LIN.	SSI	B-A*	Al/Al	1371	22.0	1	45.5
DC AMP	SSI	B-A*	Al/Al	1285	9.0	0	(<111.1)
VOLT REG	SSI	B-A*	Al/Al	439	6.8	0	(<147.1)
VOLT COMP	SSI	B-A*	Al/Al	611	5.7	0	(<175.4)
OP AMP	SSI	B-A*	Al/Al	543	4.6	0	(<217.4)
LIN.	SSI	B-A*	Al/Al	314	2.9	1	344.8
OP AMP	SSI	B-A*	Al/Al	90	2.8	3	(<1071.4)
VOLT COMP	SSI	B-A*	Al/Al	159	4.4	0	(<227.3)
OP AMP	SSI	B-A*	Al/Al	321	1.7	0	(<588.2)
LIN.	SSI	B-A*	Al/Al	1316	5.1	6	1176.5

*Special Testing - See Text

**Vendor Peculiar Problem - See Text

TABLE 2.1-14.SOURCE I SPECIAL TEST DATA*

LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
TTL	SSI	B	Al/Al	200	2.6	0	(<385.)
TTL	MSI	B	Al/Al	200	2.6	0	(<385.)
TTL	MSI	B	Al/Al	200	2.6	0	(<385.)
TTL	SSI	B	Al/Al	200	2.6	0	(<385.)

*Cycled.

TABLE 2.1-15.SOURCE J FIELD DATA

LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
DIG.	-	A	Al/Al	7700	31.	0	(<32.3)
DIG.	-	A	Al/Al	-	472.	0	(<2.1)

TABLE 2.1-16.SOURCE K SPECIAL TEST DATA

LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
RTL	SSI	B	Al/Al	1250	87.6	0	(<11.4)
RTL	SSI	B	Al/Al	2382	166.9	1	6.0
RTL	SSI	B	Al/Al	1002	70.2	0	(<14.2)
RTL	SSI	B	Al/Al	949	66.5	2	30.1
RTL	SSI	B	Al/Al	1002	70.2	0	(<14.2)
RTL	SSI	B	Al/Al	450	31.5	0	(<31.7)
RTL	SSI	B	Al/Al	2992	209.7	0	(<4.8)

TABLE 2.1-17. MISSILE H FIELD DATA

FUNCTION OR LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
TTL	SSI	B	Al/Al	5355	85.1	0	(<11.8)
TTL	SSI	B	Al/Al	7497	119.1	1	8.4
TTL	MSI	B	Al/Al	19278	306.3	0	(<3.3)
TTL	SSI	B	Al/Al	1071	17.0	0	(<58.8)
TTL	SSI	B	Al/Al	7497	119.1	0	(<8.4)
TTL	SSI	B	Al/Al	8568	136.1	0	(<7.3)
OP AMP	SSI	B	Al/Al	37485	597.6	1	1.67
DC AMP	SSI	B	Al/Al	14994	239.0	1	4.18
DC AMP	SSI	B	Al/Al	18207	290.3	1	3.44

TABLE 2.1-18. MISSILE I FIELD DATA

FUNCTION OR LOGIC TYPE	COM-PLEXITY	QUALITY LEVEL	METAL/ WIRE	NUMBER DEVICES	PART HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
TTL	SSI	B	Al/Al	16560	164.7	1	6.1
TTL	MSI	B	Al/Al	4140	41.2	0	(<24.3)
TTL	MSI	B	Al/Al	26910	267.7	1	3.7
TTL	SSI	B	Al/Al	16560	164.7	0	(<6.1)
TTL	SSI	B	Al/Al	10350	103.0	0	(<9.7)
OP AMP	SSI	B	Al/Al	51750	514.8	2	3.9
OP AMP	SSI	B	Al/Al	2070	20.6	1	48.5
OP AMP	SSI	B	Al/Al	8280	82.4	2	23.7
DUAL COMP	SSI	B	Al/Al	26910	267.7	1	3.7

TABLE 2.1-19.

MOS SSI/MSI DEVICE NON-OPERATING DATA

Quality Level	Ambient Temperature	Metal/Inter-conn.	Complex.	Part Stor. Hrs.x 10^6	No. of Failures	Fail.Rate in Fits
A	150°C	Al/Al	SSI	.015	0	(<66667.)
			MSI	.017	5	299401.
D	125°C	Al/Al	MSI	.206	24	121654.
	140°C	Al/Al	SSI	.011	1	88889.
	150°C	Al/Al	SSI	2.232	2	896.
			MSI	.084	0	(<11905.)
C	150°C	Al/Au	MSI	.100	0	(<10000.)
D	130°C	Al/Au	MSI	.510	1	1961.
	150°C	Al/Au	SSI	.108	0	(<9259.)
			MSI	.242	1	4127.
	250°C	Al/Au	SSI	.057	1	17544.
	300°C	Al/Au	SSI	.110	15	136363.
	350°C	Al/Au	SSI	.062	31	497592.

TABLE 2.1-20.

MOS SSI/MSI DEVICE REPORTED FAILURE MODES & MECHANISMS

No. Reported	Mode or Mechanism
5	Drift
10	Open
1	Short
1	Field Oxide Short
2	Gate Oxide Short
1	Lid Seal Defective
2	Al Wire Bond Defects
6	Au Ball Bond Defects
2	Al/Au Kirkendall Voids
1	Die Bond Defect
1	Resistive Junction
19	Contamination
2	Foreign Particles

2.1.3.4 Memories

Data on two major categories of monolithic memories was collected: random-access memories (RAMS) and read only memories (ROMS). Complex (larger than dual 8-bit) static and dynamic shift registers were included with the RAM data.

Data on RAMS consisted of 3 million hours of storage data roughly equivalent to field storage with no failures reported. In addition, approximately 5 million hours of high temperature storage life data with 76 device failures was reported.

Data on ROMS consisted entirely of high temperature storage life data with slightly more than 1 million hours and 25 failures reported.

The storage data collected is summarized in Tables 2.1-21 through 2.1-23. Data is given by quality level, storage temperature, complexity, metallization/interconnection system and logic type.

Failure modes or mechanisms for 55 of the storage life test failures were reported. These modes and mechanisms are listed in Table 2.1-24.

TABLE 2.1-21. RANDOM-ACCESS MEMORIES (RAMS)
NON-OPERATING DATA
(ALUMINUM METALLIZATION/ALUMINUM WIRE SYSTEM)

QUALITY LEVEL	TEMP	BITS	LOGIC	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
C	150°C	1024	MOS	.050	0	(<20000.)
D	85°C	64	MOS	.400	0	(<2500.)
D	125°C	256	TTL	.139	7	50360.
		16	MOS	.384	0	(<2600.)
		64	MOS	.180	18	(<100000.)
		256	MOS	.226	2	8850.
		1024	MOS	.040	0	(<25000.)
D	150°C	8	TTL	.025	0	(<40000.)
		16	TTL	.252	0	(<3968.)
		64	TTL	.015	0	(<66700.)
		-	MOS	.038	0	(<26300.)
		32	MOS	.028	0	(<35700.)
		64	MOS	.034	0	(<29400.)
		256	MOS	.620	4	6450.
D	160°C	256	MOS	.015	0	(<66700.)
		1024	MOS	.015	0	(<66700.)

TABLE 2.1-22. RANDOM-ACCESS MEMORIES (RAMS)
NON-OPERATING DATA
(ALUMINUM METALLIZATION/GOLD WIRE SYSTEM)

QUALITY LEVEL	TEMP	BITS	LOGIC	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
D	85°C	20	MOS	.220	0	(<4545.)
		21	MOS	2.200	0	(<454.)
		dual 25	MOS	.220	0	(<4545.)
	125°C	-	MOS	.034	0	(<29400.)
		256	MOS	.375	0	(<2667.)
		512	MOS	.288	34	118000.
		1024	MOS	.218	0	(<4590.)
	130°C	-	MOS	.040	0	(<25000.)
		20	MOS	.470	0	(<2128.)
		21	MOS	.360	0	(<2778.)
		dual 25	MOS	.300	0	(<3333.)
		64	MOS	.060	0	(<16700.)
	150°C	20	MOS	.160	1	6250.
		dual 16	MOS	.054	0	(<18500.)
		64	MOS	.051	0	(<19600.)
		1024	MOS	.036	0	(<26700.)
		64	TTL	.104	0	(<9615.)
	160°C	256	MOS	.100	0	(<10000.)
		1024	MOS	.144	0	(<6969.)

TABLE 2.1-23. READ ONLY MEMORIES (ROMS)
NON-OPERATING DATA

QUALITY LEVEL	TEMP	BITS	LOGIC	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
(ALUMINUM METAL/ALUMINUM WIRE SYSTEM)						
C	180°C	1256	Schottky TTL	.019	0	(<52600.)
	150°C	512	TTL	.092	0	(<10870.)
		8256	TTL	.022	0	(<45400.)
D	125°C	64	Schottky TTL	.529	23	43500.
		2048	MOS	.058	0	(<17000.)
	150°C	1024	Schottky TTL	.050	2	40000.
		-	RTL	.211	0	(<4740.)
		1024	MOS	.018	0	(<57100.)
	160°C	64	Schottky TTL	.025	0	(<40000.)
		2048	MOS	.005	0	(<200000.)
(ALUMINUM METAL/GOLD WIRE SYSTEM)						
B	160°C	256	Schottky TTL	.025	0	(<40000.)
D	150°C	2560	MOS	.052	0	(<19300.)
		-	MOS	.068	0	(<14700.)
	160°C	2048	MOS	.025	0	(<40000.)

TABLE 2.1-24.

MEMORIES REPORTED FAILURE MODES AND MECHANISMS

	No. of Units	Mode or Mechanism
RAMS - Al Metal/Al Wire	?	Oxide Pinhole
	18	Gate Oxide Pinhole
	1	Field Oxide Pinhole
	2	Contamination
RAMS - Al Metal/Au Wire	2	Gate Oxide Pinhole
	1	Field Oxide Pinhole
	31	Contamination
ROMS - Al/Metal/Al Wire	?	Wire Bond Defects
ROMS - Al Metal/Au Wire	- None Reported	

2.2 Monolithic Integrated Circuits Operational Prediction Models

The MIL-HDBK-217B general failure rate model for monolithic integrated circuits is:

$$\lambda_p = \Pi_L \Pi_Q (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

where:

λ_p = device failure rate
Π_L = learning adjustment factor
Π_Q = quality adjustment factor
C_1 & C_2 = Complexity Factors
Π_T = Temperature Adjustment Factor
Π_E = Environmental Adjustment Factor

The various types of microelectronic devices require different values for each of these factors. The specific factor values for each type of device are shown in Figures 2.2-1 through 2.2-7.

In the title description of each monolithic device type, SSI, MSI, and LSI represent Small Scale Integration, Medium Scale Integration, and Large Scale Integration respectively, and indicate the complexity level for which the device model is applicable. MOS represents all metal-oxide semiconductor microcircuits which includes NMOS, PMOS, CMOS, and MNOS fabricated on various substrates, such as sapphire, polycrystalline, or single crystal silicon.

Since different models are designated for the SSI/MSI and LSI Monolithic Digital devices, the following distinction in terms of complexity level is made in order to provide guidance in selection of the appropriate model. For the present, and until a new limit is established, devices having complexities less than 100 gates (approximately 400 transistors) are to be considered as SSI/MSI devices. More complex devices by gate count (or transistor count at 4 per gate) are to be considered as LSI devices. No distinction is made between SSI and MSI Monolithic Digital devices since the same model applies directly to both. Also, no distinction is made between the complexity factors for MOS and Bipolar devices in that the factors that define complexity are independent of the specific technologies.

For the purposes of this handbook, a gate is considered to be any one of the following logic functions: AND, OR, NAND, NOR, Exclusive OR, and Inverter. A J-K or R-S flip-flop is equivalent to 8 gates when used as part of a complex circuit. When the flip-flop is individually packaged (single, dual, or greater) the gate count should be determined from the schematic or logic diagram. For guidance in symbols used for these functions, see Standard ANSI Y32.14-1973, "Graphic Symbols for Logic Diagrams." This standard has been adopted by the Department of Defense and supersedes Mil-Std-806B (an earlier logic symbol standard).

Monolithic memories, because of their high gate-to-pin ratio, are not treated as a part of the SSI/MSI/LSI models. Their complexity factors are expressed in terms of the number of bits and are divided into the two major categories of monolithic memories: random-access memories (RAMS), and read-only memories (ROMS). However, for the purposes of this handbook, programmable-read-only memories (PROMS) and content-addressable memories (CAMS) are considered in the same categories as ROMS and RAMS, respectively; therefore, the same models are applicable. For complex (larger than dual 8-bit) static and dynamic shift registers, use the RAM model with bit count. For smaller shift registers, use the Digital SSI/MSI model. For linear devices, both MOS and Bipolar, the same model expressing complexity in terms of the number of transistors is presented.

Table 2.2-1 provides a list of monolithic microelectronic generic groups with a cross reference to the corresponding figure number.

The failure rate model and adjustment factors are based on certain assumptions and sub models. See Sections 2.2.1 and 2.2.2 for a description of these parameters.

2.2.1 Model Description

In order to help clarify some of the parameter descriptions for the various models, all of monolithic device models are based on a " $\lambda_T + \lambda_M$ additive model concept" -- i.e. $\lambda_P = \lambda_T + \lambda_M$,

where:

TABLE 2.2-1. MONOLITHIC MICROELECTRONIC OPERATIONAL PREDICTION MODELS CROSS REFERENCE

Monolithic Microelectronic Type	Figure No.
Bipolar Digital SSI/MSI IC's (TTL, DTL, etc., excluding Bipolar Beam Lead and Bipolar ECL)	2.2-1
Bipolar Beam Lead and Bipolar ECL Digital SSI/MSI IC's	2.2-2
Bipolar Linear SSI/MSI IC's	2.2-3
MOS Digital SSI/MSI IC's	2.2-2
MOS Linear SSI/MSI IC's	2.2-3
Bipolar Digital LSI IC's (TTL, DTL, etc., excluding Bipolar Beam Lead and Bipolar ECL)	2.2-4
Bipolar Beam Lead and Bipolar ECL Digital LSI IC's	2.2-5
MOS LSI IC's	2.2-5
Bipolar Memory IC's (TTL, DTL, etc. excluding Bipolar Beam Lead and Bipolar ECL)	2.2-6
Bipolar Beam Lead and Bipolar ECL Memory IC's	2.2-7
MOS Memory IC's	2.2-7

FIGURE 2.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL
MONOLITHIC BIPOLAR DIGITAL SSI/MSI INTEGRATED CIRCUITS
(TTL, DTL, etc. excludes Beam Lead & ECL)

$$\lambda_p = \Pi_L \Pi_Q (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.36	77	1.1	103	2.8
27	.11	53	.40	79	1.2	105	3.0
29	.12	55	.44	81	1.3	110	3.6
31	.14	57	.48	83	1.4	115	4.2
33	.15	59	.52	85	1.5	120	4.9
35	.17	61	.57	87	1.6	125	5.7
37	.19	63	.62	89	1.7	135	7.7
39	.21	65	.67	91	1.9	145	10.
41	.23	67	.73	93	2.0	155	13.
43	.25	69	.79	95	2.1	165	17.
45	.28	71	.86	97	2.3	175	22.
47	.30	73	.93	99	2.5		
49	.33	75	1.0	101	2.6		

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-35810 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Gates	C_1	C_2	No. Gates	C_1	C_2
1	.0013	.0039	46	.017	.015
2	.0021	.0050	48	.018	.016
4	.0033	.0064	50	.018	.016
6	.0043	.0074	52	.019	.016
8	.0053	.0082	54	.019	.016
10	.0061	.0089	56	.020	.017
12	.0069	.0095	58	.020	.017
14	.0077	.010	60	.021	.017
16	.0084	.011	62	.021	.017
18	.0091	.011	64	.022	.017
20	.0098	.011	66	.022	.018
22	.011	.012	68	.022	.018
24	.011	.012	70	.023	.018
26	.012	.013	72	.023	.018
28	.012	.013	74	.024	.018
30	.013	.013	76	.024	.019
32	.014	.014	78	.025	.019
34	.014	.014	80	.025	.019
36	.015	.014	85	.026	.019
38	.015	.014	90	.027	.020
40	.016	.015	95	.028	.020
42	.016	.015	99	.029	.020
44	.017	.015			

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

FIGURE 2.2-2 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL MONOLITHIC BIPOLAR BEAM LEAD, BIPOLAR ECL & MOS DIGITAL SSI/MSI INTEGRATED CIRCUITS

$$\lambda_p = \Pi_L \Pi_Q (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-35810 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Gates	C_1	C_2	No. Gates	C_1	C_2
1	.0013	.0039	46	.017	.015
2	.0021	.0050	48	.018	.016
4	.0033	.0064	50	.018	.016
6	.0043	.0074	52	.019	.016
8	.0053	.0082	54	.019	.016
10	.0061	.0089	56	.020	.017
12	.0069	.0095	58	.020	.017
14	.0077	.010	60	.021	.017
16	.0084	.011	62	.021	.017
18	.0091	.011	64	.022	.017
20	.0098	.011	66	.022	.018
22	.011	.012	68	.022	.018
24	.011	.012	70	.023	.018
26	.012	.013	72	.023	.018
28	.012	.013	74	.024	.018
30	.013	.013	76	.024	.019
32	.014	.014	78	.025	.019
34	.014	.014	80	.025	.019
36	.015	.014	85	.026	.019
38	.015	.014	90	.027	.020
40	.016	.015	95	.028	.02[illegible]
42	.016	.015	99	.029	.0[illegible]
44	.017	.015			

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.89	77	5.7	103	28.
27	.12	53	1.0	79	6.5	105	32.
29	.14	55	1.2	81	7.5	110	42.
31	.17	57	1.4	83	8.5	115	56.
33	.20	59	1.6	85	9.6	120	73.
35	.24	61	1.9	87	11.	125	94.
37	.29	63	2.2	89	12.	135	155.
39	.34	65	2.5	91	14.	145	250.
41	.40	67	2.9	93	16.	155	390.
43	.47	69	3.3	95	18.	165	610.
45	.56	71	3.8	97	20.	175	920.
47	.65	73	4.4	99	23.		
49	.76	75	5.0	101	25.		

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

FIGURE 2.2-3 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL
MONOLITHIC BIPOLAR & MOS LINEAR SSI/MSI INTEGRATED CIRCUITS

$$\lambda_p = \Pi_L \Pi_Q \left(\Pi_T C_1 + \Pi_E C_2 \right) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.89	77	5.7	103	28.
27	.12	53	1.0	79	6.5	105	32.
29	.14	55	1.2	81	7.5	110	42.
31	.17	57	1.4	83	8.5	115	56.
33	.20	59	1.6	85	9.6	120	73.
35	.24	61	1.9	87	11.	125	94.
37	.29	63	2.2	89	12.	135	155.
39	.34	65	2.5	91	14.	145	250.
41	.40	67	2.9	93	16.	155	390.
43	.47	69	3.3	95	18.	165	610.
45	.56	71	3.8	97	20.	175	920.
47	.65	73	4.4	99	23.		
49	.76	75	5.0	101	25.		

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-35810 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Trans	C_1	C_2	No. Trans	C_1	C_2
4	.0016	.0056	92	.018	.031
8	.0027	.0081	96	.018	.032
12	.0037	.010	100	.019	.032
16	.0046	.012	108	.020	.034
20	.0055	.013	116	.020	.035
24	.0063	.015	124	.022	.036
28	.0071	.016	132	.023	.038
32	.0079	.017	140	.024	.039
36	.0086	.019	148	.025	.040
40	.0093	.020	156	.026	.041
44	.010	.021	164	.027	.043
48	.011	.022	172	.028	.044
52	.011	.023	180	.029	.045
56	.012	.024	188	.030	.046
60	.013	.025	196	.031	.047
64	.014	.025	204	.032	.048
68	.014	.026	220	.034	.050
72	.015	.027	236	.036	.052
76	.015	.028	252	.038	.054
80	.016	.029	268	.040	.056
84	.016	.030	284	.042	.057
88	.017	.030	300	.043	.059

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

FIGURE 2.2-4 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL
MONOLITHIC BIPOLAR LSI INTEGRATED CIRCUITS
(TTL, DTL, etc. excludes Beam Lead & ECL)

$$\lambda_p = \Pi_L \Pi_Q \; (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for
1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-35810 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Gates	C_1	C_2	No. Gates	C_1	C_2
100	.030	.020	510	.33	.17
110	.031	.021	630	.36	.19
130	.034	.023	650	.40	.20
150	.038	.025	670	.44	.22
170	.042	.028	690	.48	.24
190	.046	.029	710	.53	.26
210	.050	.032	730	.58	.29
230	.055	.034	750	.64	.31
250	.061	.038	770	.70	.34
270	.067	.041	790	.77	.37
290	.073	.044	810	.85	.40
310	.080	.048	830	.93	.44
330	.088	.053	850	1.0	.48
350	.097	.057	870	1.1	.52
370	.11	.062	890	1.2	.56
390	.12	.068	910	1.4	.62
410	.13	.074	930	1.5	.67
430	.14	.080	950	1.6	.73
450	.16	.088	970	1.8	.79
470	.17	.095	990	2.0	.86
490	.19	.10	1050	2.6	1.1
510	.21	.11	1100	3.3	1.4
530	.23	.12	1150	4.2	1.7
550	.25	.13	1200	5.3	2.1
570	.27	.15	1250	6.7	2.6
590	.30	.16	1300	8.5	3.2

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.36	77	1.1	103	2.8
27	.11	53	.40	79	1.2	105	3.0
29	.12	55	.44	81	1.3	110	3.6
31	.14	57	.48	83	1.4	115	4.2
33	.15	59	.52	85	1.5	120	4.9
35	.17	61	.57	87	1.6	125	5.7
37	.19	63	.62	89	1.7	135	7.7
39	.21	65	.67	91	1.9	145	10.
41	.23	67	.73	93	2.0	155	13.
43	.25	69	.79	95	2.1	165	17.
45	.28	71	.86	97	2.3	175	22.
47	.30	73	.93	99	2.5		
49	.33	75	1.0	101	2.6		

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

FIGURE 2.2-5 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL MONOLITHIC BIPOLAR BEAM LEAD, BIPOLAR ECL & MOS INTEGRATED CIRCUITS

$$\lambda_p = \Pi_L \Pi_Q (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-38510 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Gates	C_1	C_2	No. Gates	C_1	C_2
100	.030	.020	610	.33	.17
110	.031	.021	630	.36	.19
130	.034	.023	650	.40	.20
150	.038	.025	670	.44	.22
170	.042	.028	690	.48	.24
190	.046	.029	710	.53	.26
210	.050	.032	730	.58	.29
230	.055	.034	750	.64	.31
250	.061	.038	770	.70	.34
270	.067	.041	790	.77	.37
290	.073	.044	810	.85	.40
310	.080	.048	830	.93	.44
330	.088	.053	850	1.0	.48
350	.097	.057	870	1.1	.52
370	.11	.062	890	1.2	.56
390	.12	.068	910	1.4	.62
410	.13	.074	930	1.5	.67
430	.14	.080	950	1.6	.73
450	.16	.088	970	1.8	.79
470	.17	.095	990	2.0	.86
490	.19	.10	1050	2.6	1.1
510	.21	.11	1100	3.3	1.4
530	.23	.12	1150	4.2	1.7
550	.25	.13	1200	5.3	2.1
570	.27	.15	1250	6.7	2.6
590	.30	.16	1300	8.5	3.2

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.89	77	5.7	103	28.
27	.12	53	1.0	79	6.5	105	32.
29	.14	55	1.2	81	7.5	110	42.
31	.17	57	1.4	83	8.5	115	56.
33	.20	59	1.6	85	9.6	120	73.
35	.24	61	1.9	87	11.	125	94.
37	.29	63	2.2	89	12.	135	155.
39	.34	65	2.5	91	14.	145	250.
41	.40	67	2.9	93	16.	155	390.
43	.47	69	3.3	95	18.	165	610.
45	.56	71	3.8	97	20.	175	920.
47	.65	73	4.4	99	23.		
49	.76	75	5.0	101	25.		

Π_E (Environment Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

FIGURE 2.2-6 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR BIPOLAR MEMORIES
(TTL, ETL etc., excludes Bipolar Beam Lead and Bipolar ECL)

$$\lambda_p = \Pi_L \Pi_Q (\Pi_T C_1 + \Pi_E C_2) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.36	77	1.1	103	2.8
27	.11	53	.40	79	1.2	105	3.0
29	.12	55	.44	81	1.3	110	3.6
31	.14	57	.48	83	1.4	115	4.2
33	.15	59	.52	85	1.5	120	4.9
35	.17	61	.57	87	1.6	125	5.7
37	.19	63	.62	89	1.7	135	7.7
39	.21	65	.67	91	1.9	145	10.
41	.23	67	.73	93	2.0	155	13.
43	.25	69	.79	95	2.1	165	17.
45	.28	71	.86	97	2.3	175	22.
47	.30	73	.93	99	2.5		
49	.33	75	1.0	101	2.6		

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-35810 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Bits	ROMS		RAMS	
	C_1	C_2	C_1	C_2
16	.0061	.0019	.011	.0033
32	.0092	.0030	.016	.0052
64	.014	.0047	.025	.0081
128	.021	.0074	.037	.013
256	.032	.012	.056	.020
320	.037	.013	.065	.023
512	.049	.018	.086	.031
576	.053	.020	.092	.034
1024	.074	.028	.13	.049
1120	.078	.030	.14	.052
1280	.085	.033	.15	.056
2048	.11	.044	.20	.076
2240	.12	.047	.21	.081
2560	.13	.051	.23	.088
4096	.17	.070	.30	.12
8192	.26	.11	.46	.19
9216	.28	.12	.49	.20
10240	.30	.13	.52	.22
12288	.33	.14	.58	.24
14848	.37	.16	.65	.27
16384	.40	.17	.69	.29

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

FIGURE 2.2-7 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR BIPOLAR BEAM LEAD, BIPOLAR ECL and MOS MEMORIES

$$\lambda_p = \Pi_L \Pi_Q \left(\Pi_T C_1 + \Pi_E C_2 \right) \times 10^{-6}$$

Π_L (Learning Factor)

Π_L = 10 for 1) a new device in initial production
2) a major change in design or process
3) extended line interruption or change in line personnel

Π_L = 1 otherwise

Π_T (Temperature Factor)

T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T	T_j (°C)	Π_T
25	.10	51	.89	77	5.7	103	28.
27	.12	53	1.0	79	6.5	105	32.
29	.14	55	1.2	81	7.5	110	42.
31	.17	57	1.4	83	8.5	115	56.
33	.20	59	1.6	85	9.6	120	73.
35	.24	61	1.9	87	11.	125	94.
37	.29	63	2.2	89	12.	135	155.
39	.34	65	2.5	91	14.	145	250.
41	.40	67	2.9	93	16.	155	390.
43	.47	69	3.3	95	18.	165	610.
45	.56	71	3.8	97	20.	175	920.
47	.65	73	4.4	99	23.		
49	.76	75	5.0	101	25.		

Π_Q (Quality Factor)

Quality Level	Π_Q
MIL-M-38510 Class A (JAN)	1
MIL-M-38510 Class B (JAN)	2
MIL-STD-883 Method 5004 Class B	5
Vendor Equiv. MIL-STD-883 Method 5004 Class B	10
MIL-M-35810 Class C (JAN)	16
Commercial Class D	150

C_1 & C_2 (Complexity Factors)

No. Bits	ROMS		RAMS	
	C_1	C_2	C_1	C_2
16	.0061	.0019	.011	.0033
32	.0092	.0030	.016	.0052
64	.014	.0047	.025	.0081
128	.021	.0074	.037	.013
256	.032	.012	.056	.020
320	.037	.013	.065	.023
512	.049	.018	.086	.031
576	.053	.020	.092	.034
1024	.074	.028	.13	.049
1120	.078	.030	.14	.052
1280	.085	.033	.15	.056
2048	.11	.044	.20	.076
2240	.12	.047	.21	.081
2560	.13	.051	.23	.088
4096	.17	.070	.30	.12
8192	.26	.11	.46	.19
9216	.28	.12	.49	.20
10240	.30	.13	.52	.22
12288	.33	.14	.58	.24
14848	.37	.16	.65	.27
16384	.40	.17	.69	.29

Π_E Environmental Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhabited	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Airborne, Uninhab.	6.0
Naval, Unsheltered	5.0
Satellite or Missile, Launch	10.0

λ_p is the overall device failure rate for monolithic devices.

λ_T is the failure rate component due to time degradation causes, and represents degradation mechanisms which are accelerated by temperature and electrical bias; composed largely of phenomena which follow the Arrhenius type rate acceleration.

λ_M is the failure rate component due to mechanical (application environment) causes, and represents failure mechanisms resulting from mechanical stresses directly, or indirectly (such as stresses set up by thermal expansion).

2.2.2 Parameters

2.2.2.1 Complexity Factors C_1 and C_2

The circuit complexity factors, C_1 and C_2, are based on the models presented below.

2.2.2.1.1 Digital SSI/MSI Devices

Tabulated values are derived from the following equations:

$$C_1 = 1.29\ (10)^{-3}(N_G)^{0.677} \qquad C_2 = 3.89(10)^{-3}(N_G)^{0.389}$$

where N_G = number of gates (assumes 4 transistors per gate).

The tabulated values are applicable to devices in packages containing up to 22 pins. For larger packages multiply the values by:

No. of Pins	Multiplier
24 to 40	1.1
42 to 64	1.2
>64	1.3

2.2.2.1.2 Linear SSI/MSI Devices

Tabulated values are derived from the following equations:

$$C_1 = .00056(N_T)^{0.763} \qquad C_2 = .0026(N_T)^{0.547}$$

where N_T = number of transistors.

2.2.2.1.3 LSI Devices

Tabulated values are derived from the following equations:

$$C_1 = .0187e^{(.00471)N_G} \qquad C_2 = .013e^{(.00423)N_G}$$

where N_G = number of gates (assume 4 transistors per gate)
and e = natural logarithm base, 2.718.

The tabulated values are applicable to devices in packages containing up to 24 pins. For larger packages, multiply values by:

No. of Pins	Multiplier
26 to 64	1.1
>64	1.2

2.2.2.1.4 Memory Devices

Tabulated values are derived from the following equations:

For ROMS - $C_1 = .00114(B)^{0.603}$ $\quad C_2 = .00032(B)^{0.646}$

For RAMS - $C_1 = .00199(B)^{0.603}$ $\quad C_2 = .00056(B)^{0.644}$

where: B = number of bits.

The tabulated values are applicable to devices in packages containing up to 24 pins. For packages with greater than 24 pins, multiply tabulated values by 1.1.

2.2.2.2 Learning Adjustment Factor, Π_L

Π_L adjusts the model for production conditions and controls. The conditions are defined in the figures for each device type.

2.2.2.3 Quality Adjustment Factor, Π_Q

Π_Q accounts for effects of different quality levels as defined in MIL-M-38510 and MIL-STD-883.

2.2.2.4 Temperature Adjustment Factor, Π_T

Π_T adjusts the model for temperature acceleration factors. Two models are applicable:

Π_{T1} is applicable to Bipolar Digital devices, i,e. TTL and DTL, not included in Π_{T2} below.

$$\Pi_{T1} = 0.1e^x$$

$$\text{where } x = -4794 \left(\frac{1}{T_j + 273} - \frac{1}{298} \right)$$

Π_{T2} is applicable to Bipolar and MOS Linear, Bipolar Beam Lead, Bipolar ECL, and all other MOS devices.

$$\Pi_{T2} = 0.1e^{x}$$

$$\text{where: } x = -8121\left(\frac{1}{T_j + 273} - \frac{1}{298}\right)$$

In Π_{T1} and Π_{T2} above, T_j is the worst case junction temperature (°C) and e is natural logarithm base, 2.718.

If T_j is unknown, use the following approximations:

For packaged monolithic devices use:

T_j = ambient T + 10°C if number of transistors ≤ 120.

T_j = ambient T + 25°C if number of transistors >120.

2.2.2.5 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in the **Appendix**.

2.3 Hybrid Integrated Circuits Storage Reliability Analysis

A hybrid integrated circuit is any combination of solid state active circuit components (IC or discrete) and of thin or thick film-deposited passive circuit elements, in combination with other compatible discrete parts when called for, interconnected by film patterns on one or more substrates in a single device package, to perform one or more circuit functions. Hybrid IC's are commonly classified as either thin or thick film.

A vapor deposited or vacuum-evaporated, or also sputtered, plated or grown film circuit is called "thin film" when the mean free path of its current carriers (mainly electrons) is comparable in length to the thickness of the film, usually in the range of a few thousand Angstroms. In practice thin film is limited to a maximum of 10,000 Angstroms (1 micron).

A film circuit deposited by screen printing (or also by spraying) with subsequent air drying and high temperature firing steps, applied in sequential cycles, is commonly known as "thick film," denoting also that its structure came about by fusing originally separated and dispersed microscopic particulate matter into a self-passivating glaze. Thick film thickness overlaps the range of thin film thickness and extends approximately to 2.5 mils (63 microns).

2.3.1 Hybrid Device Failure Mechanisms

The hybrid failure mechanisms include all those listed for the monolithic devices plus those that are unique to the hybrid technology. Hybrid devices exhibit problems as a result of the number of different materiels used in one package; the number of interconnections and bonds; the amount of processing with the chance of error or inclusion of contaminating materiels; and the hermetic sealing of a larger package. Careful selection of materiels and control of processing and temperatures are required to prevent thermal mismatches between materiels; leaching, diffusion and migration of materiels; intermetallic compound formations; and corrosion.

Tables 2.3-1 and 2.3-2 summarize the mechanisms unique to thick and thin film devices. Many of these mechanisms would be detected in formal processing and screening.

In thick film devices, the faulty substrate bond or cracked substrate which is undetected or non-failed during processing will be accelerated to failure by mechanical vibration and shock. The frequency of this failure, whether in operation or not, is dependent on the transportation and handling of the equipment in the depots and field.

The failure mechanisms for thick film resistors include those failures in processing which would slip through the screens; those that are defects which are accelerated by high temperature or thermal cycling; and those that are a result of corrosion. The two latter groups of defects may be accelerated or decelerated to failure depending on the storage environment.

The chip element failure mechanisms in thick film devices are the same as monolithic except that bonding materiels or processes may be different.

The number of conductors and interconnections in the hybrid device lead to shorted conductors, faulty bonds, etc. Most of these defects are accelerated to failure by thermal or mechanical stresses. The silver migration depends on a high current density and would be decelerated in a storage environment.

The thin film devices exhibit similar types of failure mechanisms as thick film The unique mechanisms of thin film devices are those associated with the element films. Many of these defects are accelerated to failure by thermal stresses. The rate at which defects progress to failure is dependent on the environment. The ionic migration between resistor strips is a function of high voltage and temperature and would be decelerated in a storage environment.

Most hybrid devices are custom designed for each application. The materiel selection, device design and processing for each application will determine the particular set of failure mechanisms experienced.

TABLE 2.3-1. HYBRID THICK FILM FAILURE MECHANISMS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
<u>Substrate</u>				
Faulty Substrate Bond	Insufficient or Incomplete Substrate Bonding	Mechanical Stress	Open	Electrical Test
Cracked or Broken Substrate	1) High Thermal stressed during processing	Mechanical Stress	Open	Precap visual, electrical test
	2) Thin Substrate	Mechanical Stress	Open	Precap visual, electrical test
<u>Film Resistors</u>				
Damaged Resistor	1) Overspray of abrasive trimming materiel to adjacent resistors during processing		Open or out of tolerance	Electrical Probing
	2) Electrostatic discharge during processing		Open or out of tolerance	Electrical Probing
	3) Leaching or diffusion at resistor-conductor interface	Hi Temperature	Open or out of Tolerance	
Cracked Resistor	1) Insufficient quantity of slow drying solvent, wetting agent, or flow control additive		Open	Electrical Probing
	2) Mismatch in thermal coefficient of expansion of the resistor, conductor and ceramic substrate	Thermal Cycling	Open	Electrical Probing

TABLE 2.3-1 (continued)

- HYBRID THICK FILM FAILURE MECHANISMS -

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
<u>Film Resistors</u> (cont.)				
Out-of-tolerance Resistors	1) Palladium-silver resistor change in hydrogen atmosphere		Out of tolerance	Electrical Probing
	2) Hot spots at sharp corners or resistors		Out of tolerance	Infrared scanning prior to capping
<u>Chip Elements</u>				
Faulty Bonds	1) Insufficient or incomplete bonding	Mechanical Stress	Open	Bond Pull Test, Electrical Test
	2) Leaching of silver-gold-solder combinations	Mechanical Stress	Open	Bond Pull Test, Electrical Test
	3) Glass Frit Fracture	Mechanical Stress	Open	Bond Pull Test, Electrical Test
Cracked Die	Mechanical stress during Processing	Thermal & Mechanical Stress	Open	Precap visual, Electrical Test

TABLE 2.3-1 (continued)

- HYBRID THICK FILM FAILURE MECHANISMS -

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
Conductors				
Shorted Conductors	1) Silver migration 2) Holes in glass insulation at crossover or insufficient thickness of glass.	High Current Density with potential difference	Short	Precap visual, Electrical Test
Shorted Interconnecting wires	1) Downbonding from a higher surface to a lower one	Thermal & Mechanical Stresses	Short	Precap visual, Electrical Test
	2) Improper lead length	Thermal & Mechanical Stresses	Short	Precap visual, Electrical Test
Faulty Bonds	Insufficient or Imcomplete Bonding	Thermal & Mechanical Stresses	Short	Precap visual, Electrical Test
Capacitive Coupling	Long parallel conductors resulting in capacitive coupling		Out-of-Tolerance	Electrical Test

TABLE 2.3-2.

- HYBRID THIN FILM FAILURE MECHANISMS -

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
<u>Substrate</u>				
Cracked Substrate	Thermal & Mechanical Stresses during Processing	Thermal & Mechanical Stresses	Open	Precap Visual, Substrate Capacitance Measurements, Electrical Test.
Craters or Pits in Substrate	Grain size uncontrolled and large grains pulled out during lapping, buffing or polishing.		Out-of-Tolerance	Precap visual
<u>Element Films</u>				
Drift of Electrical Parameters	1) Surface Alkali Concentrations	Thermal Cycling	Out-of-Tolerance	Electrical Test
	2) Diffusion of Alkali Ions from Substrate into resistor film	Thermal Cycling		
	3) Uneven surface			
	4) Separation of Nichrome during deposition			
	5) Thermal coefficient of expansion mismatch between film and substrate	Thermal Stresses		
	6) T_1O_2 film exhibiting semiconductor properties			
	7) Ionic migration between resistor strips	Hi Voltage & Temperature		
	8) Excess die bonding times and temperatures			

TABLE 2.3-2 (continued)

- HYBRID THIN FILM FAILURE MECHANISMS -

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
Element Films (cont.)				
Cracked or Open Element	Thermal runaway due to constriction & oxidation		Open resistor, open or shorted capacitor	Electrical Test
Shorted Capacitor	Explosion of gases during vaporization		Short	Precap visual, electrical test
Chip & Wire Bonding				
Bond Separation	1) Insufficient Bonding 2) Damage caused by probe testing	Thermal & Mechanical Stresses	Open	Precap visual, electrical test

2.3.2 Storage Reliability Data

The storage data collected on hybrid integrated circuits consists of 1,738.1 million storage hours with 61 failures reported and 0.6 million hours of accelerated storage life tests with 5 failures reported. This data represents a quality level approximately equivalent to Class B in MIL-STD-883.

Based on the number of storage hours and failures, the storage failure rate for these devices is 35.1 failures per billion hours. However, the range of types and complexities of hybrid circuits precludes the use of a single failure rate for all devices. More data will be required to adequately evaluate hybrids in the storage or non-operating environment.

The data that has been collected is summarized in Table 2.3-3. Descriptions of the data sources are the same as presented in Section 2.3.1.1.

Of the reported failures, twenty six failure causes were reported: one failed due to a failed zener diode, four due to open wire bonds; and twenty one due to open wire bonds at the aluminum/gold interface.

TABLE 2.3-3. HYBRID IC NON-OPERATING DATA

SOURCE	AMB. TEMP.	TECHNOLOGY	NO. DEVICES	STORAGE HRS. (millions)	NO. FAILURES	FAILURE RATE IN FITS
Source A	25°C	Thin Film	--	43.246	1	23.1
Source G	125°C	Thin Film	104	.09	2	20408.
	150°C	Thin Film	191	.191	3	15707.
	25°C	Thick Film	-	3.964	0	(<252.3)
	150°C	Thick Film	156	.261	2	7663.
	200°C	Thick Film	11	.011	0	(<90090.)
Source H	25°C	Thick Film	5834	38.0	0	(<26.3)
	25°C	Thick Film	36	.3	0	(<3333.3)
	25°C	Thick Film	5215	50.0	4	80.0
Source J	25°C	Thick Film	-	146.0	1	6.85
Missile H	25°C	Thick Film	62118	986.9	32	32.4
Missile I	25°C	Thick Film	2070	20.6	0	(<48.5)
	25°C	Thick Film	8280	82.4	0	(<12.1)
	25°C	Thick Film	8280	82.4	0	(<12.1)
	25°C	Thick Film	16560	164.7	13	78.9
	25°C	Thick Film	4140	41.2	9	21.8
	25°C	Thick Film	2070	20.6	0	(<48.5)
	25°C	Thick Film	2070	20.6	0	(<48.5)
	25°C	Thick Film	2070	20.6	0	(<48.5)
	25°C	Thick Film	2070	20.6	1	48.5

2.4 Hybrid Integrated Circuits Operational Prediction Model

The MIL-HDBK-217B failure rate model for hybrid microelectronic devices is:

$$\lambda_p = \lambda_b (\Pi_T \times \Pi_E \times \Pi_Q \times \Pi_F) \times 10^{-6}$$

where:

λ_b = base failure rate
Π_T = temperature factor
Π_E = environmental factor
Π_Q = quality factor
Π_F = circuit function factor

From the I.C. chip standpoint, the hybrid model is structured to accommodate all of the monolithic chip types and the various complexity levels indicated in Section 2.2.

Figure 2.4-1 gives the hybrid model and values for each parameter. The base failure rate must be calculated and a description of this calculation is given below.

2.4.1 Base Failure Rate, λ_b

The base failure rate equation is:

$$\lambda_b = \lambda_S + A_S\lambda_C + \Sigma\lambda_{RT}N_{RT} \text{ (substrate contribution)}$$

$$+ \Sigma\lambda_{DC}N_{DC} \text{ (contribution of attached components)}$$

$$+ \lambda_{PF}\Pi_{PF} \text{ (package contribution)}$$

A. Substrate Contribution

λ_S is the failure rate due to the substrate and film processing. It has a value of either 0.02 or 0.04 and is independent of the number of substrates. The value 0.02 applies if only thick film or only thin film substrates are used. The value 0.04 applies if both types are used.

$A_S\lambda_C$ is the failure rate contribution due to network complexity and substrate area. The values of λ_C (complexity term) are a function of the element density, N_E/A_S. A_S is the substrate area in square inches.

To compute complexity, A_S is obtained by summing the areas of all thick film substrates resulting in a single equivalent thick film substrate. An equivalent thin film substrate is determined similarly. However, when substrates are stacked, only the area of the bottom substrate shall be used to compute A_S. If a substrate contains only one device, it shall be considered a chip and shall not be considered a substrate for purposes of failure rate prediction.

N_E is the total complexity expressed as

$$N_E = N_{LT} + N_{RT} + N_{DC}$$

where:

N_{LT} = number of internal lead terminations. Normally, this would be 2 times the number of leads, but for beam leads and flip chips, this would be one for each connection. This includes the leads from substrate to external leads.

N_{RT} = number of film resistors

N_{DC} = number of discrete chip devices (each chip counts as one device)

As a convenience in estimating the number of terminations from the schematic, the following approximations may be used (it is always more desirable to count the actual lead terminations than to use the approximation):

N_{LT} = No. of transistors x 4
+ No. of diodes x 2
+ No. of capacitors x 4
+ No. of chip resistors x 4
+ No. of conventionally packaged integrated circuit leads x 2
+ No. of integrated circuit chip bond pads x 2
+ No. of external hybrid package leads x 2

For the single equivalent thick film substrate, the value for N_E is determined from the above rules. Then N_E/A_S is computed using the A_S obtained in accordance with the above rules. The value of failure rate per square inch, λ_C, is obtained from the following equations.

For thin film :

$$\lambda_{C1} = 4.7(10)^{-8}\left(\frac{N_E}{A_S}\right)^{2.082} \quad \text{for } 120 \leq \frac{N_E}{A_S} \leq 10{,}000$$

$$= .001 \quad \text{for } 10 \leq \frac{N_E}{A_S} \leq 120$$

For thick film:

$$\lambda_{C2} = 2.4(10)^{-14}\left(\frac{N_E}{A_S}\right)^{4.429} \quad \text{for } 250 \leq \frac{N_E}{A_S} \leq 2{,}000$$

$$= .001 \quad \text{for } 10 \leq \frac{N_E}{A_S} \leq 250$$

The final value of $A_S\lambda_C$ requires the use of the same A_S used to determine N_E/A_S.

This procedure is then repeated for the thin film equivalent substrate. It should be noted that when N_E is computed for stacked substrates, the elements of the upper substrates are included with the bottom substrate, even though the upper substrate uses a different resistor technology than the bottom substrate (thin film or thick film or vice versa).

$\underline{\Sigma N_{RT}\lambda_{RT}}$ is the sum of the failure rates for each resistor as a function of the required resistance tolerance.

N_{RT} is the number of film resistors of a given tolerance.

λ_{RT} is the failure rate to be used for each resistor of a given tolerance as specified in Figure 2.4-1.

B. Attached Components Contribution.

$\Sigma\lambda_{DC}N_{DC}$ is the sum of the attached device failure rates for semiconductors, integrated circuits, capacitors and resistors, both packaged and unpackaged. The failure rate is computed by multiplying the λ_{DC} by N_{DC}, the quantity of each type. The λ_{DC} is the same for a packaged or unpackaged device. The λ_{DC} values are in Figure 2.4-1.

C. Package Contribution.

$\lambda_{PF}\Pi_{PF}$ is the hybrid package failure rate which is a function of the package style or configuration and the materials used in its construction.

λ_{PF} is 0.01 failure/10^6 hr. This is a normalized value of base failure rate for all hybrid packages.

Π_{PF} is an adjustment factor which modifies λ_{PF} as a function of the package style and materials. Its values are in Figure 2.4-1.

2.4.2 Π Adjustment Factors

2.4.2.1 Temperature Adjustment Factor, Π_T

Π_T adjusts the model for temperature acceleration factors. The values in Figure 2.4-1 are derived from

$$\Pi_T = e^x$$

where $x = -3411 \left(\frac{1}{T + 273} - \frac{1}{298} \right)$ for Π_{T1} if the temperature (°C) of the package mounting base is known, and

$x = -3794 \left(\frac{1}{T + 273} - \frac{1}{318} \right)$ for Π_{T2} if the highest temperature (°C) within the hybrid package is known.

Π_T values are invalid at package mounting base temperatures above 125°C or for hot spot temperatures above 175°C.

2.4.2.2 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in the appendix.

2.4.2.3 Quality Factor, Π_Q

Π_Q accounts for effects of different quality levels. Classes A, B and C devices are those which have been subjected to, and passed all requirements, tests, and inspections specified in Methods 5004 and 5006 of MIL-STD-883, including screening, qualification, and quality conformance inspection requirements for the specified class.

2.4.2.4 Circuit Function Adjustment Factor, Π_F

Π_F adjusts the model for circuit function, (i.e., digital or linear).

FIGURE 2.4-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR HYBRID MICROELECTRONIC DEVICES

$$\lambda_p = \lambda_b (\Pi_T \times \Pi_E \times \Pi_Q \times \Pi_F) \times 10^{-6}$$

$$\lambda_b = \lambda_S + A_S\lambda_C + \sum\lambda_{RT}N_{RT} + \sum\lambda_{DC}N_{DC} + \lambda_{PF}\Pi_{PF}$$

λ_S (Substrate Failure Rate)

λ_S = .02 if only thick film or only thin film

λ_S = .04 if both thick film and thin film

A_S (Substrate Failure Rate Modifier)

A_S = Substrate Area in Square Inches.

λ_C (Complexity Term)

See next Page

λ_{RT} (Resistor Tolerance Factor)

Resistor Tolerance (±Percent)	Thin Film Resistors	Thick Film Resistors
0.1 to 1.0	0.00050	-
1.0 to 5.0	0.00025	0.00050
5.0	0.00010	0.00012

N_{RT} = # of Resistors of a Given Tolerance

λ_{DC} (Attached Devices Term)

See next page

N_{DC} = # of attached devices of a given type.

λ_{PF} (Package Failure Rate)

0.01

Π_{PF} (Package Factor)

Package Description	Π_{PF}
Package Type (<2.25" outer seal perimeter or <0 625" diameter)	
Flat Pack (welded lid, up to 16 leads)	1.0
Flat Pack (soldered lid, up to 16 leads)	1.5
Dual-In-Line (<16 leads)	2.0
Top Hat Type (i.e. TO-3, TO-5)	
Single Substrate	1.5
Multiple Substrate	3.0
Package Type (>2.25" outer seal perimeter or >0.625" diameter)	
Flat Pack (welded lid)	2.0
Butterfly (welded lid)	2.0
Butterfly (soldered lid)	2.5
Flat Pack (soldered lid)	2.5
Dihedral (soldered lid)	3.0
Platform (soldered lid)	4.0
Modular Packages	4.0
Multilayer Ceramic Substrates	4.0
Vertical Sidewall (cold welded lid)	5.0
Note: Forall packages with >16 leads, add 0.15 to Π_{PF} for each 4 leads >16.	

Π_T (Temperature Factor)

T(°C)	Π_{T1}	Π_{T2}	T(°C)	Π_{T1}	Π_{T2}
25	1.0	.45	105	11	6.66
30	1.2	.55	110	13	7.6
35	1.5	.68	115	14	8.6
40	1.7	.83	120	16	9.7
45	2.1	1.0	125	18	11.
50	2.4	1.2	130	-	12.
55	2.8	1.4	135	-	14.
60	3.3	1.7	140	-	16.
65	3.9	2.0	145	-	17.
70	4.5	2.4	150	-	19.
75	5.2	2.8	155	-	21.
80	6.0	3.3	160	-	24.
85	6.8	3.8	165	-	26.
90	7.8	4.4	170	-	29.
95	8.8	5.1	175	-	32.
100	10.0	5.8			

Use Π_{T1} if package mounting base Temperature is known.

Use Π_{T2} if highest temperature in package is known.

Π_E (Environment Factor)

Environment	Π_E
Ground, Benign	0.2
Space Flight	0.2
Ground, Fixed	1.0
Airborne, Inhab.	4.0
Naval, Sheltered	4.0
Ground, Mobile	4.0
Naval, Unshelt.	5.0
Airborne, Uninhab.	6.0
Missile, Launch	10.0

FIGURE 2.4-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR HYBRID MICROELECTRONIC DEVICES (continued)

λ_{DC} **(Attached Devices Failure Rate)**

Attached Device Description	λ_{DC}
Capacitor	
Ceramic, General Purpose	0.0004
Electrolytic	0.004
Inductors	0.0001
Resistor Chips	0.0002
Diode, Silicon*	
Logic Switch	0.0048
Small Signal (<500ma)	0.0081
Power Rectifier (>500ma)	0.012
Zener (volt. reg)	0.022
Thyristor	0.05
Varactor; Step Rec; Tunnel	0.19
Detector	0.18
Mixers	0.22
Transistor, Silicon*	
NPN, Logic Switch	0.0053
NPN, Linear	0.011
NPN, Power (>1W)	0.051
PNP, Logic Switch	0.0077
PNP, Linear	0.017
PNP, Power (>1W)	0.081
FET, Logic Switch	0.021
FET, Linear	0.063
Unijunction	0.10
Monolithic Microcircuits	
Bipolar digital devices (TTL & DTL types not included below)	**
Bipolar & MOS linear, bipolar beam lead, bipolar ECL and all other MOS devices.	***

*For JAN TX or TXV multiply by 0.2.
For NON-JAN/Commercial multiply by 5.
**Use monolithic models, assuming 25°C, Class B (JAN) MIL-M-38510 Quality Level, $\Pi_E = 1.0$ and $\Pi_L = 1.0$.
***Same as above and multiply by 2.

λ_C (Complexity Term)

N_E/A_S	λ_{C1} Thin F.	λ_{C2} Thick F.	N_E/A_S	λ_{C1} Thin F.	λ_{C2} Thick F.
10 to			1500	.19	2.8
120	.0010	.0010	2000	.35	10.0
150	.0016	.0010	2500	.56	-
200	.0029	.0010	3000	.82	-
250	.0046	.0010	3500	1.1	-
300	.0068	.0022	4000	1.5	-
350	.0093	.0044	4500	1.9	-
400	.012	.0080	5000	2.4	-
450	.016	.014	5500	2.9	-
500	.020	.022	6000	3.6	-
550	.024	.033	6500	4.1	-
600	.029	.048	7000	4.8	-
650	.034	.069	7500	5.5	-
700	.039	.096	8000	6.3	-
750	.045	.13	8500	7.1	-
800	.052	.17	9000	8.0	-
850	.059	.23	9500	9.0	-
900	.067	.29	10000	10.0	-
950	.074	.37			
1000	.083	.46			

$N_E = N_{LT} + N_{RT} + N_{DC}$
N_{LT} = # of Internal Lead Terminations
N_{RT} = # of Film Resistors
N_{DC} = # of Discrete Chip Devices

Π_Q (Quality Factor)

Level or Class	A	B	C
Π_Q	.5	1	30

Π_F (Circuit Function Factor)

Function	Π_F
Digital	0.8
Linear	1.0
Linear/Digital Combination	1.1

2.5 Operational/Non-Operational Failure Rate Comparison

2.5.1 Bipolar Digital and Linear SSI/MSI Devices

A comparison of the failure rates for non-operational and operational environments was made using the non-operating model and the MIL-HDBK-217B operational model. The comparison is presented in Figures 2.5-1. Failure rates for several operating conditions were predicted to present a range for comparison. The non-operating prediction was made at a nominal ambient temperature of 25 degrees centigrade.

Comparing the digital devices with aluminum metallization and aluminum wire gave an operating to non-operating ratio of 6 and 8 for Class A, small scale integration (SSI), digital devices at two operating junction temperatures: 35°C and 75°C; for Class B the ratios were 3 and 5; for Class C devices, 22 and 29; and for Class D, 82 and 108.

For medium scale integration (MSI), the ratios for Class A were 15 and 24; Class B, 8 and 14; Class C, 51 and 84; and Class D, 193 and 317.

Comparing the linear devices with aluminum metallization and aluminum wire gave an operating to non-operating ratio of 10 and 25 for Class A, small scale integration (SSI), linear devices at two operation junction temperatures: 35°C and 75°C; for Class B the ratios were 6 and 14; for Class C devices, 36 and 88; and for Class D, 133 and 329.

For medium scale integration (MSI), the ratios for Class A were 37 and 125; Class B, 21 and 71; Class C, 133 and 443; and Class D, 501 and 1662.

Failure rates for digital devices with aluminum metallization and gold wire were also compared. Since MIL-HDBK-217B uses one prediction model for both metallization systems, the operating failure rates are the same. For the non-operating failure rate, the aluminum metallization, gold wire systems exhibited a significantly higher failure rate, therefore the ratios are considerably different - so different that in some cases, the non-operating failure rate is higher than the operating failure rate. The ratios for Class A, SSI Digital devices at the two junction temperatures are 0.6 and 0.8; for Class B, 0.4 and 0.5; for C, 2.2 and 2.9 and for Class D, 0.7 and 0.9.

For MSI devices, the ratios for Class A were 1.5 and 2.4; Class B, .8 and 1.4; Class C, 5.2 and 8.5; and Class D, 1.6 and 2.6.

Failure rates for linear devices with aluminum metallization and gold wire were also compared. For the non-operating failure rate, the aluminum metallization, gold wire systems exhibited a significantly higher failure rate, therefore the ratios are considerably different - so different that in some cases, the non-operating failure rate is higher than the operating failure rate. The ratios for Class A, SSI linear devices at the two junction temperatures are 1.0 and 2.5; for Class B, 0.6 and 1.4; for Class C, 3.6 and 8.8 and for Class D, 1.1 and 2.8.

For MSI devices, the ratios for Class A were 3.8 and 12.5; Class B, 2.2 and 7.1; Class C, 13.4 and 44.4; and Class D, 4.2 and 13.9.

Since most missile materiel are in the Class B or Class A quality range, average operating to non-operating factors can be defined as presented in Table 2.5-1.

DIGITAL OPERATING FAILURE RATES PER MIL-HDBK-217B*(GROUND FIXED ENVIRONMENT)

QUALTIY CLASS	CONDITION 1	CONDITION 2	CONDITION 3	CONDITION 4	PARTS COUNT
A	5.4	12.7	7.1	20.8	14.5
B	10.7	25.4	14.2	41.6	29.0
C	85.7	202.9	113.6	332.8	232.0
D	803.5	1901.9	1065.0	3120.0	2175.0

Condition 1
T_J = 35°C, 2 Gates
Condition 2
T_J = 35°C, 20 Gates
Condition 3
T_J = 75°C, 2 Gates
Condition 4
T_J = 75°C, 20 Gates

NON-OPERATING FAILURE RATE & NON-OPERATING/OPERATING RATIO

ALUMINUM METALLIZATION, ALUMINUM WIRE:

QUALITY CLASS	NON-OP FAILURE RATE*	RATIO CONDITION 1	RATIO CONDITION 2	RATIO CONDITION 3	RATIO CONDITION 4	PARTS COUNT
A	.875	6	15	8	24	17
B	3.06	3	8	5	14	9
C	3.94	22	51	29	84	59
D	9.84	82	193	108	317	221

ALUMINUM METALLIZATION, GOLD WIRE:

QUALITY CLASS	NON-OP FAILURE RATE*	RATIO CONDITION 1	RATIO CONDITION 2	RATIO CONDITION 3	RATIO CONDITION 4	PARTS COUNT
A	8.7	.6	1.5	.8	2.4	1.7
B	30.5	.4	.8	.5	1.4	1.0
C	39.3	2.2	5.2	2.9	8.5	5.9
D	1177.7	.7	1.6	.9	2.6	1.8

*Failures per Billion Hours.

FIGURE 2.5-1. MONOLITHIC BIPOLAR DIGITAL DEVICE OPERATIONAL/
NON-OPERATIONAL FAILURE RATE COMPARISON

LINEAR OPERATING FAILURE RATES PER MIL-HDBK-217B* (GROUND FIXED ENVIRONMENT)

QUALITY CLASS	CONDITION 1	CONDITION 2	CONDITION 3	CONDITION 4	PARTS COUNT
A	8.7	32.8	21.6	109.0	26.0
B	17.5	65.7	43.2	218.0	52.0
C	140.0	525.4	345.6	1744.0	416.0
D	1312.0	4926.0	3240.0	16330.0	3900.0

Condition 1
T_j = 35°C, 8 transistors
Condition 2
T_j = 35°C, 80 trabsistors
Condition 3
T_j = 75°C, 8 transistors
Condition 4
T_j = 75°C, 80 transistors

NON-OPERATING FAILURE RATE & NON-OPERATING/OPERATING RATIO

ALUMINUM METALLIZATION, ALUMINUM WIRE:

QUALITY CLASS	NON-OP FAILURE RATE*	RATIO CONDITION 1	RATIO CONDITION 2	RATIO CONDITION 3	RATIO CONDITION 4	PARTS COUNT
A	.875	10	37	25	125	30
B	3.06	6	21	14	71	17
C	3.94	36	133	88	443	106
D	9.84	133	501	329	1662	396

ALUMINUM METALLIZATION, GOLD WIRE:

QUALITY CLASS	NON-OP FAILURE RATE*	RATIO CONDITION 1	RATIO CONDITION 2	RATIO CONDITION 3	RATIO CONDITION 4	PARTS COUNT
A	8.7	1.0	3.8	2.5	12.5	3.0
B	30.5	.6	2.2	1.4	7.1	1.7
C	39.3	3.6	13.4	8.8	44.4	10.6
D	1177.7	1.1	4.2	2.8	13.9	3.3

*Failures per Billion Hours.

FIGURE 2.5-2. MONOLITHIC BIPOLAR LINEAR DEVICE OPERATIONAL/ NON-OPERATIONAL FAILURE RATE COMPARISON

TABLE 2.5-1.

AVERAGE OPERATING TO NON-OPERATING FAILURE RATE
RATIO ALUMINUM METALLIZATION/
ALUMINUM WIRE

COMPLEXITY LEVEL	AVERAGE OPERATING TO NON-OPERATING FAILURE RATE RATIO	
	---Digital---	---Linear---
SSI	5	14
MSI	14	71

ALUMINUM METALLIZATION/GOLD WIRE

COMPLEXITY LEVEL	AVERAGE OPERATING TO NON-OPERATING FAILURE RATE RATIO	
	---Digital---	---Linear---
SSI	.5	1.4
MSI	1.4	7.1

The quality factors in the non-operating prediction model for a device with aluminum metal/gold wire systems were estimated from the aluminum metal/aluminum wire system.

2.5.2 Hybrid IC Devices

A comparison of the failure rates for non-operational and operational environments was made based on two hybrid circuits representative of the non-operating data. The operational failure rates were calculated from the MIL-HDBK-217B operational model as shown in Figure 2.5-2. For the digital circuit, a failure rate of 81 fits was calculated and 559 fits for the linear circuit. The average non-operating failure rate for these devices was 35.1 fits, therefore, the operating to non-operating ratio for these circuits range from 2.3 to 15.9.

FIGURE 2.5-2

OPERATIONAL FAILURE RATE CALCULATION FOR TWO HYBRID CIRCUITS

	Circuit 1	Circuit 2
Package Type	20 pin metal flat pack	22 pin metal flat pack
Substrate Size	.412 x .37 (one layer)	.7 x .665 (one layer)
Internal Lead Terminations	70	106
Internal Chips		
4-2 gate	1	
Op Amp		4
NPN, Si, SW Trans.	4	
NPN, Si, Lin. Trans.		4
PNP, Si, SW Trans.	4	
PNP, Si, Lin. Trans.		4
Signal, Si, Diode	6	3
Ceramic Capacitor	2	2
Film Resistors ±5%	10	26
Environment	Ground Fixed	Ground Fixed
Temperature	25°C (ambient)	25°C (ambient)
Screen Class	B	B
Technology	Thick	Thick
Calculation		
λ_S	.02	.02
N_C	95.	141.
Λ_S	.15244	.4655
N_C/Λ_S	623.2	302.9
λ_C	.048	.0022
$\Lambda_S \lambda_C$	.00732	.001
$\Sigma N_{rt} \lambda_{rt}$	.0012	.00312
$\Sigma N_{dc} \lambda_{dc}$	.0460	.50806
$\lambda_{pf} \pi_{pf}$	.0265	.02725
λ_b	.101	.559
λ_p	.081	.559

2.6 Conclusions and Recommendations

The models presented in section 2.1 for monolithic bipolar SSI/MSI digital and linear integrated circuits can be used as a method of prediction failure rates for these devices.

The analysis indicates that a single metal should be used for the contact metallization and interconnection interface. The all-aluminum system shows a definitely more reliable storage capability than the aluminum metallization/gold wire system. Data on the Beam Lead Sealed Junction device with gold beams is not available on the linear devices.

In both user surveys and high temperature storage tests, wire bond failures were prominant.

For the aluminum metallization/aluminum wire systems, the principle problems were wire bonds and oxide defects or contamination.

Screens or tests recommended for wire bonds include centrifuge, temperature shock/cycling, power cycling, mechanical shock and bond pull tests. Due to the low mass of aluminum wires, the temperature shock/cycle, power cycle, and bond pull tests would be most effective.

Screens or tests recommended to weed out oxide defects include: Operating AC and DC with temperature; high temperature reverse bias; power cycling; elevated temperature storage; and visual inspection.

In the MIL-STD-883 screen, temperature cycling is required for Class A, B and C devices while temperature shock is only required for Class A devices. Burn-in and final electrical tests at maximum and minimum operating temperatures are required for Class A and B devices. Reverse bias burn-in is only required for Class A MOS and linear devices when specified. Visual inspection is required for Class A and B devices.

Depending on whether Class A, B or C devices are specified in the procurement, it may be desirable to specify more screens and/or quality conformance tests which are related to wire bond and oxide reliability.

Effects of periodic testing or operational cycling of devices which are in a storage or dormant environment has not been addressed here. The data does not identify the effects of cycling. One special test was performed to determine cycling effects on 1000 digital devices but after 18 months, no failures were experienced. The testing was performed under controlled conditions.

Lack of sufficient data on LSI devices, MOS devices and memories precludes any conclusions on these devices.

2.7 Reference

2.7.1 Report LC-78-IC1, "Monolithic Bipolar SSI/MSI Digital & Linear Integrated Circuit Analysis"

The information presented for digital and linear devices is a summary of document number LC-78-IC1, "Monolithic Bipolar SSI/MSI Digital & Linear Integrated Circuit Analysis," dated January 1978. Refer to this document for details of the data collection and analysis, development of models, definition of failure mechanisms, and technical description of the devices themselves.

2.7.2 Report DD14-23, Reliability Factors for Electronic Components in a Storage Environment

The data analyzed in Sections 2.1 through 2.6 is on devices stored for up to nine years. A separate study has been conducted on microelectronic failure mechanisms for up to twenty years storage time by the Georgia Institute of Technology. This report, prepared for the U. S. Army Missile Research and Development Command, considers physical and chemical properties of the electronic devices and the environments in which a device may be subjected from processing through twenty years of field storage. Conclusions from this report are contained below. For details, the reader is referred to Report DD14-23, "Reliability Factors for Electronic Components in a Storage Environment," by B. R. Livesay and E. J. Scheibner, Applied Sciences Laboratory, Engineering Experiment Station, Georgia Institute of Technology, September, 1977.

1. The most important environmental forcing functions, or stresses, in storage are mechanical, chemical and low thermal. Mechanical stresses occur due to thermal-mechanical interactions and residual stresses. Chemical stresses result from contaminants such as residual process chemicals and environmental gases which are introduced through improper or failed seals. Although purely thermal stresses have much less importance in storage than operating environments, certain low temperature reaction rates and diffusion processes are temperature dependent.

2. The synergism of the three primary storage stresses is critical. Any one of the three acting alone may not be particularly damaging but the combined effect of two or three forcing functions acting together is likely to cause device failures.

3. Environmental extremes for Army missiles in storage have involved temperatures of -50°C to +75°C, diurnal cycling of 70°C, 100 percent relative humidity, direct sea spray, industrial pollutants, some mechanical shock and fungus.

4. The failure mechanisms of greatest importance in storage have been identified as those related to various marginal manufacturing mistakes, corrosion processes and mechanical fracture. Electrical or potential current induced degradation processes should not be important in the storage environment. Moisture within a package is probably the most important factor for both corrosion and mechanically induced failures in storage. Chemicals including moisture trapped within a package due to improper cleaning or because of evolution from materials such as polymers are a critical concern for long-term reliability. The package seal is also critical for keeping out atmospheric contaminants. Thermal-mechanical stresses aided by chemical agents will cause crack propagation in seals, passivation layers, bonds, metallization layers and the silicon chip.

5. New manufacturing methods such as the Tape Automated Bonding technology should be continually evaluated to determine if there are potential storage failure mechanisms. For example, are there detrimental effects in a storage environment from probable impurities introduced during bump plating and bonding operations?

6. The presence of defects such as impurities, dislocations, microcracks, interfacial faults and grain boundaries in the materials of a microcircuit structure can result in failure due to low temperature atomic diffusion processes.

7. The design of circuit configurations along with the choice of materials for electronic systems placed in storage should be based on a sound understanding of potential degradation processes in expected storage environments.

8. Particulate matter is one of the dominant concerns as a storage failure mechanism.

9. The hermeticity of microelectronic packages is an important concern for long-term storage conditions. The screen test for determining the effectiveness or hermeticity of the package seals includes a fine leak rate test. The maximum allowable leak rate specified for this test should be lowered to 10^{-10} atm cm^3 sec^{-1} for devices that are expected to be stored because of the exchange of gases between the initial package ambient and the external storage environment for packages with a finite size leak.

10. All microcircuit packages should be vacuum baked at 150°C for at least 4 hours and sealed in dry nitrogen without ever being exposed to moisture containing gases such as air. The moisture content of the nitrogen sealing chamber should be less than 100 ppm.

11. Significant improvements are needed in the measurement technology for moisture and other gases in microcircuit packages. Current methods are too expensive and complicated while providing insufficient sensitivity and wide variations in numerical values for supposedly identical gas contents.

12. The fields across a thin gate oxide in MOS devices can often approach the dielectric strength of the oxide. However, because of various factors that are not easily controlled the breakdown voltages have a range of values. Consequently, any application of potentials to the gate electrode can be a possible cause of oxide breakdown, particularly when static charging is not avoided or if there are voltage transients present in ground test equipment.

13. The use of plastics introduces high risks of differential expansion problems which result in mechanical damage such as pulling apart leads.

14. Whenever polymeric materials are employed for die attach within hybrid microcircuit packages, they must be proved compatible with all enclosed electronic materials. No chlorine or other halogen containing materials should be sealed in any

circuitry components. Polymers used should be simple hydrocarbons or compounds of carbon, hydrogen and oxygen. Nitrogen containing polymers should be considered with skepticism. The responsibility for proof of compatibility should be with the manufacturer for specific epoxies and circuit element combinations.

15. Missiles placed in storage should never contain electronic parts employing polymers for package seals. Polymers will transmit moisture and other gases.

16. Screening and accelerated testing procedures of Army missiles must have steps determined by potential storage failure processes. There is doubt that the screening sequence contained in MIL-STD-883A is fully appropriate to the storage environment.

17. There is widespread controversy about the optimum number of cycles in a temperature cycling screen test. Opinions vary from 25-300 cycles for effective screening but the use of only 10 cycles is not considered to be of any value. Results of the Rockwell International screen test program have not resolved this question.

18. Thermal shock should never be used as a screen test stress for hermetic devices placed in stored missile systems.

19. The metallurgical consequences of an upper limit of 150° vs. 125°C for temperature cycling and stabilization bakes with regard to solders should be investigated.

20. High temperature burn-in is a relatively effective screen for failure modes having high activation energies. For oxide defects the failure mode has a much lower activation energy. The high temperature burn-in is then not particularly useful. An over-voltage stress should be investigated for screening MOS devices for oxide defects.

21. Complex MOS/LSI microcircuits require a different approach to reliability than mere application of MIL-STD-883 screens. Attention to good quality control at the process level and the development of more appropriate screens are essential to improved reliability. In addition, the use of a specially designed

process evaluation circuit providing device materials parameters at the wafer level should be required for high reliability devices. This circuit should also be useful for developing and evaluating the effectiveness of screens.

22. The philosophy necessary for developing meaningful screen testing parameters is to concentrate on determining the stress-duration levels required to reveal well defined device faults. The capability is therefore needed for fabricating devices with deliberate defects of desired type, severity and number.

23. Only general environmental data are currently available for the temperature, environmental gases, vibration, etc. expected in storage. There is need for specific information concerning the interior of a missile in storage in order to make judgments concerning future reliability factors. The chemical factors associated with moisture, evolved gases and fungus need to be developed at four levels:

1. Within the storage structure (igloo, shed, etc.)
2. Within the missile container
3. Within the missile electronic system compartment
4. Within individual component packages.

A measurement program should be established so that actual data will be available concerning these factors.

24. The effectiveness of desiccant materials used within Army missiles should be evaluated. This topic was not pursued during this program but questions were raised by several organizations.

25. The various types of missile storage containers should be evaluated to determine how well they protect missiles from storage environments most critical to the electronic systems.

26. Procedures should be in effect to close the loop concerning the detailed analysis of parts failing in service and manufacturing parameters. Failures in field environments are generally more severe than indicated by initial predictions. Feed-back from service failures should be available to guide design decisions of future systems.

27. Future efforts in storage reliability should be directed towards determining the response of materials in microcircuit structures to the storage environmental forcing functions. This will require the application, and in some cases, the development of advanced measurement techniques in order to determine chemical, mechanical and thermal threshold levels for device degradation processes. Particular emphasis should be placed on quantitative evaluations of moisture induced failure processes so that contaminant requirements can be established. The basic threshold levels for degradation have to be established before effective screens and accelerated test methods can be designed.

28. Measurements of permeabilities, diffusion coefficients, and solubilities of water in representative polymers should be made so that good data are available and effects of temperature, pressure, mechanical strain, previous sorption, and synergism of two or more penetrants be understood. Data on thermal expansion, glass transitions, and viscoelastic responses of polymer encapsulants and adhesives are too meager for design of circuit systems. Measurements are needed here.

29. Age sensitive materials used in missile systems must be well characterized. Missile storage reliability is determined by the stability of the materials used to fabricate individual parts within the system while exposed to the storage environment of a tactical missile. There is a strong need for compiling material degradation data from the technical literature, directed experiments and theoretical calculations.

2.7.3 Report MDC E1601 Final Report - Storage Reliability of Missile Materiel

The report documents another study performed for the U. S. Army Missile Research & Development Command. The study conducted accelerated life tests on selected missile parts to provide a "before the fact" indication of storage reliability potential. It assessed twenty-one part types, including both "active" parts (integrated circuits, transistors, and diodes) and passive parts (resistors, capacitors, and inductors). The objectives of the program are as follows:

- To generate and execute designed experiment test plans for accelerating the failure mechanisms and inducing failures relating to non-operating and storage conditions for selected items of microelectronic and semiconductor hardware.
- To analyze the data obtained from accelerated testing of the selected items, using such techniques (but not limited to) as the Arrhenius model and regression analysis to generate meaningful predictions of failure rates (MTBF) for the devices under actual storage conditions.
- To determine by use of Analysis of Variance Techniques (or other suitable techniques) the relative effects of quantitative and qualitative variables on the reliability of the tested material when subjected to long non-operating periods.

A brief summary of the results are shown in Table 2.7-1.

For details the reader is referred to Report MDC E1601, Final Report - Storage Reliability of Missile Materiel, McDonnell Douglas Astronautics Company - East, 29 April, 1977.

TABLE 2.7-1. ACCELERATED LIFE TESTS SUMMARY RESULTS

	ITEM		LIFE TEST FAILURE PERCENTAGE	MAJOR LIFE TEST FAILURE MECHANISMS		ACTIVATION ENERGY (eV)		FAILURE DISTRIBUTION	[1] $\lambda(t)_{MAX}$ FAILURES/HOUR	RECOMMENDATIONS
				DESCRIPTION	PERCENTAGE OF TOTAL FAILURES	FREAK	MAIN			
CATEGORY 1										
	256 BIT RANDOM ACCESS MEMORY		62.0%	MOBILE ION DRIFT	12.9%	---	---	---	---	
				CATION DRIFT	41.9%	0.5 [3]	1.0 [3]	LOGNORMAL	4.3×10^{-5} [5]	YES
				ALUMINUM SPEARING	39.8%	---	---	---	---	
	OPERATIONAL AMPLIFIER		36.0%	MOBILE ION DRIFT	98.1%	---	3.09	LOGNORMAL	1.8×10^{-18} [5]	YES
	VOLTAGE REGULATOR		28.0%	MOBILE ION DRIFT	97.6%	1.36	2.01	LOGNORMAL	3.25×10^{-10} [5]	YES
	LOW POWER SWITCH		69.3%	MOBILE ION DRIFT OR SURFACE STATES	100%	---	1.81	LOGNORMAL	5.66×10^{-6}	YES
	NPN LOW POWER AMPLIFIER		75.7%	INCREASE IN SURFACE STATE DENSITY	78%	2.07	2.24	LOGNORMAL	6.97×10^{-15}	YES
				MOBILE ION DRIFT	18.9%	---	---	---	---	
	N CHANNEL FET		36.5%	MOBILE ION DRIFT	69.4%	0.11	0.67	LOGNORMAL	1.3×10^{-6} [5]	YES
	TANTALUM CHIP CAPACITOR		40.0%	DIELECTRIC DEGRADATION	61%	---	1.27	WEIBULL	1.13×10^{-6}	YES
	CERAMIC AXIAL LEAD CAPACITOR		78%	MATERIAL DEGRADATION	98%	---	1.18	WEIBULL	9.4×10^{-10}	NO
	HIGH SELF-RESONANT FREQUENCY INDUCTOR CHIP		40%	INSULATION DIFFUSION	84%	---	2.93	LOGNORMAL	4.4×10^{-10}	YES
	FERRITE BEAD INDUCTOR		52.0%	INSULATION DIFFUSION	100%	---	1.31	LOGNORMAL	5.1×10^{-14}	YES
	SPECIAL HYBRID SUBSTRATE		13.7%	NOT ESTABLISHED	100%	---	1.91	WEIBULL	2.96×10^{-10}	NO
CATEGORY 2										
	LOW POWER AMPLIFIER		7.3%	HEADER BURRS	82%	---	0.43	LOGNORMAL [4]	2.9×10^{-10} [4]	YES
	CERAMIC CHIP RESISTOR		2.0%	NOT ESTABLISHED	100%		0.27	LOGNORMAL [4]	3.3×10^{-6} [4]	YES

TABLE 2.7-1. ACCELERATED LIFE TESTS SUMMARY RESULTS (cont'd)

	ITEM		LIFE TEST FAILURE PERCENTAGE	MAJOR LIFE TEST FAILURE MECHANISMS		ACTIVATION ENERGY (eV)		FAILURE DISTRIBUTION	$\lambda(t)_{MAX}$ △1 FAILURES/HOUR	RECOMMENDATIONS
				DESCRIPTION	PERCENTAGE OF TOTAL FAILURES	FREAK	MAIN			
CATEGORY 3										
	QUAD 2-INPUT NAND GATE		3.3%	BEAM TO DIE SHORT	60%	---	---	△2	△2	NO
	DUAL 4-INPUT MULTIPLEXER		1.3%	LIFTED Al-Al BOND	100%	---	---	△2	△2	NO
	QUAD 2-INPUT NAND BUFFER		8.7%	MULTIPLE	---	---	---	△2	△2	NO
	60 GATE RAYPACK CHIP		3.3%	MULTIPLE	---	---	---	△2	△2	NO
	GENERAL PURPOSE SWITCH		3.3%	MOBILE ION DRIFT	40%	---	---	△2	△2	NO
	HIGH CURRENT SWITCH		43.1%	GOLD SCAVENGING	93.5%	---	---	△2	△2	YES
	PORCELAIN CHIP CAPACITOR		3.3%	SILVER SCAVENGING	100%	---	---	△2	△2	NO
	CERAMIC CHIP CAPACITOR		2.0%	NOT DETERMINED	100%	---	---	△2	△2	NO

△1 MAXIMUM CALCULATED INSTANTANEOUS FAILURE RATE FOR A 20 YEAR STORAGE PERIOD (TEMPERATURE RANGE: 25°C TO 100°C).

△2 INSUFFICIENT FAILURES (OR APPLICABLE FAILURES) FOR FAILURE DISTRIBUTION ANALYSIS - NO OBVIOUS PARAMETER DEGRADATION TRENDS.

△3 THESE ARE ASSUMED VALUES. INSUFFICIENT DATA FOR ARRHENIUS EVALUATION.

△4 PARAMETER DEGRADATION TREND ALLOWED EXTRAPOLATION OF TIMES TO FAILURE.

△5 BASED ON OPERATIONAL CONDITION. STORAGE FAILURE RATE SHOULD BE MANY ORDERS OF MAGNITUDE LESS.

△6 CATEGORY 1 - PARTS HAVING SUFFICIENT LIFE TEST FAILURES FOR FAILURE DISTRIBUTION/FAILURE RATE ANALYSIS.

CATEGORY 2 - PARTS WITH FEW LIFE TEST FAILURES BUT DISPLAYING AN OBVIOUS PARAMETER DEGRADATION TREND ALLOWING FAILURE TIME EXTRAPOLATION.

CATEGORY 3 - PARTS HAVING NO PARAMETER DEGRADATION TRENDS AND TOO FEW FAILURES (OR APPLICABLE FAILURES) FOR FAILURE DISTRIBUTION/FAILURE RATE ANALYSIS.

BIBLIOGRAPHY

RADC-TR-70-232, Reliability Characterization and Prediction of Integrated Circuits, the Boeing Company, D. C. Porter and W. A. Finke, dated November 1970, AD 878235

TM-72-1, Microcircuit Wire Bond Reliability, Reliability Analysis Center, T. R. Meyers, dated July 1972, AD 746315

MCR-72-169, Long Life Assurance Study for Manned Spacecraft Long-Life Hardware, Martin Marietta, R. W. Burrows, dated September 1972

RADC-TR-67-108, Vol. II, RADC Reliability Notebook, Hughes Aircraft Co., Clifford M. Ryerson, et al, dated September 1967

RADC-TR-65-330, Reliability Physics Notebook, dated October 1965

RADC-TR-73-248, Dormancy and Power On-Off Cycling Effects on Electronic Equipment and Part Reliability, Martin Marietta, J. A. Bauer, et al, dated August 1973

GIDEP Summaries of Failure Rate Data, dated January 1974 (Supplement dated September 1975)

MDR-1, RAC Microcircuit Device Reliability, Digital Generic Failure Rates, Dated,Summer,1975

MDR-6, RAC Microcircuit Device Reliability, Linear/Interface Data, dated,Autumn, 1977

RADC-TR-69-350, Failure Rate for Complex Bipolar Microcircuits, AFSC, Peter F. Manno, dated October 1969, AD 861045

RADC-TR-72-55, Reliability Problems with S102 Passivation and Glassivation, RADC, Clyde H. Lane, dated March 1972, AD 741765

MIL-M-38510A, General Specifications for Microcircuits, dated 3 July 1972

MIL-STD-883, Test Methods and Procedures for Microelectronics, dated 3 July, 1972

N71-19422, Beam Lead Technology, GTE Labs, T. W. Fitzgerald, et al, dated 15 March 1971

RADC-TR-71-294, Microcircuit Bond Screening Study, Raytheon, John Gaffrey and Bennie Bonomi, dated December 1971, AD 892498

99900-6735-RO-00, Appraisal of Microelectronic Integrated Circuit Performance, TRW, G. A. Van Hoorde, dated October 1968.

BR-7811, The Environmental Conditions Experienced by Rockets and Missiles in Storage, Transit, and Operations, Raytheon, James M. Durben and Edward T. Smith, dated December 1973.

EPIC-IR-81, Materiels and Interface Factors Limiting LSI Performance and Reliability, Hughes Aircraft, Thomas C. Hall, et al, dated August 1972

Metallurgical Failure Modes of Wire Bonds, George G. Harmon, National Bureau of Standards, 12th Annual Proceedings IEEE Reliability Physics Symposium, 1974

MIL-HDBK-217B, Reliability Prediction, dated 20 September 1974

Aging Effects in Gold Thermocompression Bonds to Complex Metallizations, J. H. Anderson, Jr., et al, IEEE Transactions on Reliability, Vol. R-19, No. 1, February 1970

Elements of Semiconductor-Device Reliability, C. Gordon Peattre, et al, Proceedings of the IEEE, Vol. 62, No. 2, February 1974

Reliability Assurance of Individual Semiconductor Components, Raymond F. Haythornthwaite, et al, Proceedings of the IEEE, Vol. 62, No. 2, February 1974

Failure Analysis of Oxide Defects, G. H. Ebel and H. A. Engelke, 11th Annual Proceedings IEEE Reliability Physics Symposium, 1973

Metallization and Bonds - A Review of Failure Mechanisms, G. L. Schnable and R. S. Keen, Sixth Annual Reliability Physics Symposium Proceedings, 1967

Raytheon Memo No. DATA:77:059, from A. D. Luna, Subject: Dormant Failure Rate Update No. 9, dated 23 March 1977

Telecon Report, Mr. Bill Johnson, General Electric, Subject: Site Defense System Study, dated 6 March 1975

Sandia Letter from Mr. J. A. Hood, Subject: Semiconductor Reliability Assessment, dated 23 September 1974

UCLA - ENG. 7359, Interface Phenomena in Integrated Circuit Oxides, C. R. Viswanathan, University of California, Los Angeles, July 1973

Technical Note 1972-20, Procurement of Reliable Semiconductor Devices for Military Space Applications, Alan G. Stanley, Massachusetts Institute of Technology, 3 April 1972

The Storage of Microelectronic Integrated Circuits, Weapons Quality Engineering Center, Naval Weapons Support Center, Crane, Indiana, July 1977

Report No. DD14-23, Reliability Factors for Electronic Components in a Storage Environment, B. R. Livesay, E. J. Scheibner, Georgia Institute of Technology, Sept. 1977

Report LC-76-IC1, Monolithic Bipolar SSI/MSI Digital Integrated Circuit Analysis, D. Malik, Raytheon Co., May 1976

Report LC-76-IC2, Monolithic Bipolar SSI/MSI Linear Integrated Circuit Analysis, D. Malik, Raytheon Co., May 1976

3.0 Discrete Semiconductors

This section contains a summary of the analyses and data on discrete semiconductors-transistors and diodes. Being special types of semiconductors, failure modes and mechanisms affecting transistors and diodes are similar to those found in other semiconductors discussed in Section 2.1. Also applicable are the causes, accelerating environments and detection methods. That information is well covered in Section 2.1 and will not be repeated in detail. Only differences between discrete semiconductors and integrated circuits will be discussed.

3.1 Storage Reliability Analysis

3.1.1 Failure Mechanisms

The failure mechanisms, causes, accelerating environments and detection methods characteristic of transistors are found in Table 2.1-2. As in all semiconductors, transistors do not appear to have failure mechanisms inherent to the concept of the device. All of the mechanisms are initiated by deficiencies in the materials and fabrication processes used during manufacture of the devices.

The difference between discrete transistors and integrated circuits lies in the physical size and number and complexity of manufacturing processes. Compared to the average integrated circuit, a transistor is a relatively simple device. There are fewer number of junctions and leads. The distances between different parts of the device are larger. The manufacturing processes are fewer and simpler. Although the failure mechanisms are similar to those in integrated circuits, the above differences tend to shift their emphasis. Bulk defects are more common due to the larger blocks of silicon required thus increasing the probability of crystal imperfections. Imperfections collect mobilized contaminants resulting in breakdown, leakage, gain failures and, in high power devices, thermal runaway. Diffusion defects are not as critical due to the lower density of diffusions. Oxide and metallization defects are not as pronounced as in integrated circuits because the metallization patterns are much simpler.

A large percentage of transistor failures are the result of die and wire bonding defects. Contamination, both ambient and within the material, is also a serious problem in transistors.

The failure mechanisms of diodes are similar to those found in transistors. The mechanisms, causes, accelerating environments and detection methods presented in Table 2.1-2 apply and will not be repeated here. In addition to those mechanisms in Table 2.1-2, alloy bonded and point contact diodes can develop intermetallic compounds at the junction, however, this has not been noticed to be a severe problem. Loss of contact is also a potential problem in spring loaded contacts. This happens when the contact material loses its compression strength or by slipping off the contact.

3.1.2 Discrete Semiconductor Non-Operational Prediction Models

The non-operational failure rate model for discrete semiconductors is:

$$\lambda_p = \lambda_b (\Pi_Q \times \Pi_E) \times 10^{-6}$$

where: λ_p = device failure rate
λ_b = base failure rate
Π_Q = quality adjustment factor
Π_E = environmental adjustment factor

The model and values for Silicon NPN & PNP and Germanium NPN & PNP Transistors are presented in Figure 3.1-1; and for Field Effect Transistors in Figure 3.1-2.

Non-operating data on Unijunction transistors was insufficient to develop a non-operating prediction at this time.

The model and values for General Purpose Silicon and General Purpose Germanium Diodes are presented in Figure 3.1-3; for Zener and Avalanche Diodes in Figure 3.1-4; and for Microwave Diodes in Figure 3.1-5.

Non-operating data on thyristors and varactors was insufficient to develop a non-operating prediction at this time.

In the models, the base failure rate, λ_b, is 1.76 fits (failures per billion hours) for silicon transistors; 1.15 fits for field effect transistors;1.51 fits for general purpose diodes; and 0.31 fits for Zener and Avalanche Diodes; and 2.45 fits for microwave diodes.

The quality adjustment factor, Π_Q, accounts for effects of the quality levels (JAN and JANTX) as defined in MIL-S-19500.

The environmental adjustment factor, Π_E, accounts for the influence of factors other than temperature. Refer to the environmental description in the Appendix.

FIGURE 3.1-1. NON-OPERATIONAL FAILURE RATE PREDICTION MODEL FOR TRANSISTORS (Includes Silicon NPN & PNP, and Germanium NPN & PNP)

$$\lambda_p = \lambda_b \, (\Pi_Q \times \Pi_E) \times 10^{-6}$$

λ_b (Base Failure Rate)

$\boxed{0.00176}$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	0.17
JAN	1.0

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

FIGURE 3.1-2. NON-OPERATIONAL FAILURE RATE PREDICTION MODEL FOR FIELD EFFECT TRANSISTORS

$$\lambda_p = \lambda_b (\Pi_Q \times \Pi_E) \times 10^{-6}$$

λ_b (Base Failure Rate)

$$\boxed{0.00115}$$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	0.2
JAN	1.0

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

FIGURE 3.1-3. NON-OPERATIONAL FAILURE RATE PREDICTION MODEL FOR GENERAL PURPOSE SILICON & GERMANIUM DIODES

$$\lambda_p = \lambda_b \, (\Pi_Q \times \Pi_E) \times 10^{-6}$$

λ_b (Base Failure Rate)

$\boxed{0.00151}$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	0.064
JAN	1.0

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

FIGURE 3.1-4. NON-OPERATIONAL FAILURE RATE PREDICTION AND MODEL FOR ZENER AND AVALANCHE DIODES

$$\lambda_p = \lambda_b (\Pi_Q \times \Pi_E) \times 10^{-6}$$

λ_b (Base Failure Rate)

$\boxed{0.00031}$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	1.0
JAN	1.0

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

FIGURE 3.1-5. NON-OPERATIONAL FAILURE RATE PREDICTION AND MODEL FOR MICROWAVE DIODES

$$\lambda_p = \lambda_b (\Pi_Q \times \Pi_E) \times 10^{-6}$$

λ_b (Base Failure Rate)

$\boxed{0.00245}$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	.6
JAN	1.0

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	10
Airborne, Inhabited	50
Naval, Sheltered	50
Ground, Mobile	50
Naval, Unsheltered	50
Airborne, Uninhab.	80
Missile, Launch	200

3.1.3 Non-Operating Failure Rate Data and Analysis

3.1.3.1 Transistors

The failure rate models in Section 3.1.2 are based on storage data consisting of approximately 25 billion hours with 54 failures reported. This includes data from nine different programs. The breakdown of storage hours and failures for each source is shown in Tables 3.1-2 through 3.1-10. In cases where definition of device type and application was not possible, the data was aggregated into a "general" category.

The aggregation of storage hours and failures from all nine programs is summarized in Table 3.1-1. This table presents the aggregated data for both JANTX and JAN rated devices.

Analysis of this data together with the parameters in the MIL-HDBK-217B model indicated very little difference between the failure rates of silicon NPN and PNP transistors.

The storage data indicated a difference between JAN and JANTX device failure rates in the operational and non-operational environments. While the MIL-HDBK-217B operational model shows a factor of five, the storage data indicated a factor of 6+. Field effect transistor data indicates for JANTX devices to be in the same general failure rate range as the silicon NPN and PNP devices. Very little JAN data was available on the field effect transistors and a factor of 5 from MIL-HDBK-217B was used.

Insufficient data on unijunction transistors is available for analysis.

3.1.3.2 Diodes

The failure rate tables in Section 3.1.2 are based on storage data consisting of over 38 billion part hours with 65 failures reported. This includes data from eight sources. The breakdown of storage hours and failures for each program is shown in Tables 3.1-12 through 3.1-19. In cases where the definition of device type and application was not possible, the data was aggregated into a "general" category.

The aggregation of storage hours and failures from all three programs is shown in Table 3.1-11.

Analysis of this data together with the parameters in the MIL-HDBK-217B model indicated very little difference between the failure rates of silicon and germanium general purpose diodes.

The storage data did indicate a greater difference between JAN and JANTX device failure rates than in the operational environment. While the operational model shows a factor of 5, the storage data indicates a factor of 15+.

The present storage data on zener diodes does not show a difference between the JAN and JANTX devices. The JANTX data shows 4 failures in approximately 1.8 billion hours for a storage failure rate of 3.12 fits while the JAN data shows no failures in 0.8 billion storage hours for a failure rate of less than 1.2 fits. This rate is approximately six times that of the silicon general purpose diodes JANTX quality.

Only JANTX data was available on microwave diodes showing a failure rate of 32.6 fits.

Insufficient data on thyristor and varactor diodes is available for analysis.

3.1.3.3 Transistor and Diode Data Sources

Missile D data consists of 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes approximately 2 billion transistor storage hours with 2 failures, and 0.6 billion diode storage hours with one failure. The transistor failure records indicated one degraded transistor and one catastrophically failed. The diode failure mode was reported as open.

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included 766 million transistor part hours with 4 failures reported and 1.7 billion diode storage hours with 8 failures reported. All of the devices in Missile E-1 are rated MIL-STD.

Missile F data consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southeast desert under open sided metal roof sheds; 30 missiles stored outside in the canal zone under open sided metal roof sheds; and 30 missiles stored in the southeast U. S. in bunkers. The data includes 160 million transistor storage hours with no failures reported and 168 million diode storage hours with no failures reported.

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. The data includes 57 million transistor storage hours with no failures, and 84 million diode storage hours with no failures.

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. The data includes 10 billion transistor storage hours with 12 failures reported, and 5 billion diode storage hours with 4 failures reported.

Missile I data consists of 2.070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. The data includes more than 4.6 billion transistor storage hours with 12 failures reported and 5.1 billion diode storage hours with 3 failures reported.

Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual sources. The data for source A is summarized for transistors in Table 3.1-8 for for diodes in Table 3.1-18. Both MIL-STD and HI-REL devices were included.

Source D represents a special test program on devices stored in an environmentally controlled warehouse for up to 5 years. Over 44 million transistor storage hours and 26 million diode storage hours were investigated with one diode failure.

Source E represents a second special test program with 15.9 million transistor storage hours with one failure recorded. The storage was in an environmentally controlled facility.

TABLE 3.1-1. TRANSISTOR NON-OPERATING DATA SUMMARY

DEVICE TYPE & QUALITY LEVEL	STORAGE HRS. $x 10^6$	NUMBER FAILED	STORAGE HRS. $x 10^6$	NUMBER FAILED	λ IN FITS	90% ONE-SIDED CONFIDENCE λ IN FITS
Silicon						
PNP (JAN)	25.5	0	2268.1	20	8.82	11.9
NPN (JAN)	408.3	1				
General (JAN)	1834.3	19				
PNP (JANTX)	3357.6	5	19959.0	30	1.51	1.92
NPN (JANTX)	5697.0	11				
Dual NPN (JANTX)	1385.2	1				
PNPN (JANTX)	51.1	0				
General (JANTX)	9468.1	13				
FET						
(JAN)			25.5	0	<39.2	90.6
(JANTX)			2616.3	3	1.15	2.55
Germanium						
PNP (JANTX)	58.1	0	79.1	0	<12.6	29.2
NPN (JANTX)	21.0	0				
Unijunction						
(JANTX)			1.3	0	<769.2	1777.
Microwave						
(JANTX)			17.0	1	58.8	228.9

TABLE 3.1-2. MISSILE D TRANSISTOR NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon				
PNP	40227	489.8	0	(<2.04)
NPN	9858	120.0	1	8.33
Dual NPN	108915	1326.2	1	0.75
PNPN	3816	46.5	0	(<21.5)

TABLE 3.1-3. MISSILE E-1 TRANSISTOR NON-OPERATING DATA (JAN)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon				
PNP	1748	25.5	0	(<39.2)
NPN	27968	408.3	1	2.45
General	20976	306.3	3	9.79
FET, N Channel	1748	25.5	0	(<39.2)

TABLE 3.1-4. MISSILE F TRANSISTOR NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Germanium				
PNP	600	13.1	0	(<76.3)
Silicon				
NPN	3120	68.3	0	(<14.6)
Dual NPN	1800	39.4	0	(<25.4)
PNP	1800	39.4	0	(<25.4)

TABLE 3.1-5. MISSILE G TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon				
PNP	390	11.2	0	(<89.3)
NPN	546	15.7	0	(<63.7)
General	1053	30.2	0	(<33.1)

TABLE 3.1-6. MISSILE E TRANSISTOR NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon				
NPN	321300	5104.4	8	1.04
Dual NPN	5355	85.1		
PNP	145656	2314.0		
Dual PNP	10710	170.1		
NFET	130662	2075.8	3	1.20
Dual NFET	21420	340.3		
PFET	5355	85.1		
Microwave Power	1071	17.0	1	58.8

TABLE 3.1-7. MISSILE I TRANSISTOR NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon				
NPN	140760	1400.1	4	2.86
PNP	149040	1482.5	4	2.70
Dual	2070	20.6	0	<48.5
FET	4140	41.2	0	<24.3
General	169740	1688.4	4	2.37

TABLE 3.1-8. SOURCE A TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Transistors JANTX All Data		10662	12	1.13
Silicon PNP (All)		1327	1	.75
Low Power		686	1	1.46
Medium Power		189	0	(<5.30)
High Power		452	0	(<2.21)
Silicon NPN (All)		4076	6	1.47
Low Power		3036	4	1.32
Medium Power		249	0	(<4.01)
High Power		791	2	2.53
Germanium NPN		21	0	(<48.0)
Germanium PNP		45	0	(<22.32)
FET		72	0	(<13.95)
Unijunction		1	0	(<973.)
Transistors JAN All Data		1528	16	10.47

TABLE 3.1-9. SOURCE D TRANSISTOR NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon NPN (All)	547	16.911	0	(<59.1)
Single	315	10.005	0	(<99.9)
Dual	232	6.906	0	(<144.8)
Silicon PNP	239	7.669	0	(<130.4)
Silicon PNPN	30	.562	0	(<1779.)
Unijunction	10	.317	0	(<3154.)
FET	55	1.883	0	(<531.1)

TABLE 3.1-10. SOURCE E TRANSISTOR NON-OPERATING DATA (JANTX)

DEVICE TYPE	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
General	15.9	1	62.89

TABLE 3.1-11. DIODE NON-OPERATING DATA SUMMARY

DEVICE TYPE & QUALITY LEVEL	STORAGE HOURS x 10^6	NUMBER FAILED	TYPE	STORAGE HOURS x 10^6	NUMBER FAILED	λ IN FITS	90% ONE-SIDED CONFIDENCE λ IN FITS
Silicon, General Purpose							
(JAN)	7348.6	43	JAN	7833.5	49	6.26	7.55
(JANTX)	9388.7	2					
General							
(JAN)	484.9	6	JANTX	27254.4	8	0.29	0.48
(JANTX)	17865.7	6					
Zener							
(JAN)	785.6	0	JAN & JANTX	2560.9	4	1.56	3.12
(JANTX)	1775.3	4					
Silicon Controlled Rectifier							
(JANTX)				509.2	1	1.96	7.64
Microwave Power							
(JANTX)				204.2	3	14.7	32.6
Tunnel							
(JANTX)	2.0	0		4.0	0	(<250.)	577.4
Varactor							
(JANTX)	2.0	0					

TABLE 3.1-12. MISSILE D DIODE NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, General Purpose	954	11.6	0	(<86.2)
Zener	6678	81.3	0	(<12.3)
Silicon Controlled Rectifier	41817	509.2	1	1.96

TABLE 3.1-13. MISSILE E-1 DIODES NON-OPERATING DATA (JAN)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, General Purpose	74290	1084.6	2	1.84
Zener	12230	178.6	0	(<5.60)
General	33212	484.9	6	12.4

TABLE 3.1-14. MISSILE F DIODE NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, General Purpose	7440	162.9	0	(<6.14)
Zener	240	5.3	0	(<188.7)

TABLE 3.1-15. MISSILE G DIODE NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, General Purpose	2340	67.1	0	(<14.9)
Zener	351	10.1	0	(<99.0)
General	234	6.7	0	(<149.3)

TABLE 3.1-16. MISSILE H DIODES NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, General Purpose	274176	4355.8	0	(<0.23)
Zener	22491	357.3	1	2.80
Microwave Power	12852	204.2	3	14.7

TABLE 3.1-17. MISSILE I DIODES NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, General Purpose	480240	4776.9	2	0.42
Zener	465750.	411.8	1	2.43

TABLE 3.1-18. SOURCE A DIODES NON-OPERATING DATA

	JAN			JANTX		
DEVICE TYPE	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, Gen. Purpose	6262.	41	6.54	-	-	-
Zener	607.	0	(<1.65)	898.	1	1.11
Tunnel	-	-	-	2.	0	(<523.)
Varactor	-	-	-	2.	0	(<523.)
General	-	-	-	17859.	6	0.34

TABLE 3.1-19. SOURCE D DIODES NON-OPERATING DATA (JANTX)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Silicon, Gen. Purpose	465	14.403	0	(<69.4)
Zener	377	11.491	1	87.0

3.2 Discrete Semiconductor Operational Prediction Models

The MIL-HDBK-217B general failure rate model for transistors and diodes is:

$$\lambda_p = \lambda_b\ (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_{S2} \times \Pi_C) \times 10^{-6}$$

Where:

λ_p = device failure rate
λ_b = base failure rate
Π_E = Environmental Adjustment Factor
Π_A = Application Adjustment Factor
Π_Q = Quality Adjustment Factor
Π_{S2}= Voltage Stress Adjustment Factor
Π_C = Complexity Adjustment Factor

The various types of semiconductors require different failure rate models that vary to some degree from the basic model. The specific failure rate model and the Π factor values for each group are shown in figures 3.2-1 thru 3.2-15.

The base failure rate and adjustment factor values presented in the figures are based on certain assumptions. See section 3.2.1 and 3.2.2 for a description of these parameters.

Table 3.2-1 provides a list of the semiconductor generic groups with a cross reference to the corresponding figure number.

3.2.1 Base Failure Rate (λ_b)

The equation for the base failure rate, λ_b, is:

$$\lambda_b = Ae^{\left(\frac{N_T}{273 + T + (\Delta T)\ S}\right)} e^{\left(\frac{273 + T + (\Delta T)\ S}{T_M}\right)^P}$$

Where

A is a failure rate scaling factor.

e is the natural logarithm base, 2.718

N_T, T_M and P are shaping parameters.

T is the operating temperature in degrees C, ambient or case, as applicable (see Section 3.2.3 for instructions).

ΔT is the difference between maximum allowable temperature with no junction current or power (total derating) and the maximum allowable temperature with full rated junction current or power.

TABLE 3.2-1 DISCRETE SEMICONDUCTOR OPERATIONAL PREDICTION MODELS CROSS REFERENCE

DISCRETE SEMICONDUCTOR TYPE	GROUP	FIGURE #
Silicon NPN Transistors	I	3.2-1
Silicon PNP Transistors	I	3.2-2
Germanium PNP Transistors	I	3.2-3
Germanium NPN Transistors	I	3.2-4
Field Effect Transistors	II	3.2-5
Unijunction Transistors	III	3.2-6
Silicon (General Purpose) Diodes	IV	3.2-7
Germanium (General Purpose) Diodes	IV	3.2-8
Voltage Regulator & Voltage Reference (Temp. Compensated)(Zener, Avalanche) Diodes	V	3.2-9
Thyristors	VI	3.2-10
Silicon Microwave Detectors	VII	3.2-11
Germanium Microwave Detectors	VII	3.2-12
Silicon Microwave Mixers	VII	3.2-14
Varactors, Step Recovery & Tunnel Diodes	VIII	3.2-15

S is the stress ratio of operating electrical stress to rated electrical stress (see Section 3.2.3 for S calculation).

The values for the constant parameters are shown in Table 3.2-2. The resulting base failure rates as functions of temperature and electrical stress are shown for each part type in Figures 3.2-1 through 3.2-15. These failure rates are based on the typical maximum junction temperatures (fully derated) of 100 degrees C for germanium (70 degrees C for microwave types) and 175 degrees C for silicon (150 degrees C for microwave types) as well as a value of 25 degrees C for the maximum temperature at which full rated operation is permitted. If device temperature ratings are different from these values, see Section 3.2.3 for S calculations to compensate for these differences.

The base failure rate tables contain failure rates up to full rated conditions. If a particular operating condition of S and T is high enough to fall into a blank portion of the table, the device is <u>over-rated</u> and should not be used.

3.2.2 Π Adjustment Factors

3.2.2.1 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environmental description in the Appendix.

3.2.2.2 Application Adjustment Factor, Π_A

Π_A accounts for effect of application in terms of circuit function.

3.2.2.3 Quality Adjustment Factor, Π_Q

Π_Q accounts for effects of different quality. The quality levels (JAN, JANTX, JANTXV) are as defined in MIL-S-19500.

TABLE 3.2-2
DISCRETE SEMICONDUCTOR BASE FAILURE RATE PARAMETERS

Group	Part Type	λ_b Constants				
		A	N_T	T_M	P	ΔTr
Transistors						
I	Si, NPN	0.13	-1052	448	10.5	150
	Si, PNP	0.45	-1324	448	14.2	150
	Ge, PNP	6.5	-2142	373	20.8	75
	Ge, NPN	21.	-2221	373	19.0	75
II	FET	0.52	-1162	448	13.8	150
III	Unijunction	3.12	-1779	448	13.8	150
Diodes						
IV	Si, Gen. Purp.	0.9	-2138	448	17.7	150
	Ge, Gen. Purp.	126	-3568	373	22.5	75
V	Zener/Avalanche	0.04	-800	448	14	150
VI	Thyristors	0.82	-2050	448	9.6	150
VII	Microwave					
	Ge, Detectors	0.33	-477	343	15.6	45
	Si, Detectors	0.14	-392	423	16.6	125
	Ge, Mixers	0.56	-477	343	15.6	45
	Si, Mixers	0.19	-394	423	15.6	125
VIII	Varactor, Step Recovery & Tunnel	.93	-1162	448	13.8	150

3.2.2.4 Voltage Stress Adjustment Factor, Π_{S2}

Π_{S2} adjusts the model for a second electrical stress (application voltage) in addition to wattage included in the base failure rate, λ_b. The voltage stress, S2, is defined as:

$$S2 = \frac{\text{Applied } (V_{CE})}{\text{Rated } (V_{CEO})} \times 100$$

3.2.2.5 Complexity Adjustment Factor, Π_C

Π_C accounts for effect of multiple devices in a single package. Each transistor in a case must be treated individually for complexity factor. Its failure rate, λ_b, modified by other Π factors and then multiplied by this complexity factor. If only one transistor of a pair is used, treat as an independent item with $\Pi_C = 1.0$.

FIGURE 3.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR SILICON NPN TRANSISTORS

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_{S2} \times \Pi_C) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0034	.0041	.0048	.0057	.0067	.0079	.0095	.011	.014	.018
10	.0038	.0046	.0054	.0064	.0075	.0089	.010	.013	.017	.023
20	.0043	.0051	.0060	.0071	.9984	.010	.012	.015	.020	.029
25	.0046	.0054	.0064	.0075	.0089	.010	.013	.017	.023	.033
30	.0048	.0057	.0067	.0079	.0095	.011	.014	.018	.025	
40	.0054	.0064	.0075	.0089	.010	.013	.017	.023	.033	
50	.0060	.0071	.0084	.010	.012	.015	.020	.029		
55	.0064	.0075	.0089	.010	.013	.017	.023	.033		
60	.0067	.0079	.0095	.011	.014	.018	.025			
65	.0071	.0084	.010	.012	.015	.020	.029			
70	.0075	.0089	.010	.013	.017	.023	.033			
75	.0079	.0095	.011	.014	.018	.025				
80	.0084	.010	.012	.015	.020	.029				
85	.0089	.010	.013	.017	.023	.033				
90	.0095	.011	.014	.018	.025					
95	.010	.012	.015	.020	.029					
100	.010	.013	.017	.023	.033					
105	.011	.014	.018	.025						
110	.012	.015	.020	.029						
115	.013	.017	.023	.033						
120	.014	.018	.025							
125	.015	.020	.029							
130	.017	.023	.033							
135	.018	.025								
140	.020	.029								
145	.023	.033								
150	.025									
155	.029									
160	.033									

Π_Q **(Quality Factor)**

Quality Level	Π_Q
JANTXV	.2
JANTX	.4
JAN	2.0
Lower	10.0

Π_{S2} **(Voltage Stress Factor)**

S_2 (percent)	Π_{S_2}
100	3.0
90	2.25
80	1.65
70	1.2
60	1.0
50	0.75
40	0.48
30	0.36
20	0.30
10	0.30
0	0.30

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_C **(Complexity Factor)**

Complexity	Π_C
Single Transistor	1.0
Dual (Unmatched)	0.7
Dual (Matched)	1.2
Darlington	0.8
Dual Emitter	1.1
Multiple Emitter	1.2
Complementary Pair	0.7

Π_A **(Application Factor)**

Application	Π_A
Linear	1.5
Logic Switch	0.7
High Frequency (R.F. >400 MHz)	5.0

FIGURE 3.2-2 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR SILICON PNP TRANSISTORS

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_{S2} \times \Pi_C) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0045	.0057	.0070	.0085	.010	.012	.014	.018	.022	.030
10	.0053	.0065	.0080	.0096	.011	.013	.016	.021	.027	.039
20	.0061	.0075	.0091	.010	.013	.015	.019	.024	.034	.053
25	.0065	.0080	.0096	.011	.013	.016	.021	.027	.039	.063
30	.0070	.0085	.010	.012	.014	.018	.022	.030	.045	
40	.0080	.0096	.011	.013	.016	.021	.027	.039	.063	
50	.0091	.010	.013	.015	.019	.024	.034	.053		
55	.0096	.011	.013	.016	.021	.027	.039	.063		
60	.010	.012	.014	.018	.022	.030	.045			
65	.010	.013	.015	.019	.024	.034	.053			
70	.011	.013	.016	.021	.027	.039	.063			
75	.012	.014	.018	.022	.030	.045				
80	.013	.015	.019	.024	.034	.053				
85	.013	.016	.021	.027	.039	.063				
90	.014	.018	.022	.030	.045					
95	.015	.019	.024	.034	.053					
100	.016	.021	.027	.039	.063					
105	.018	.022	.030	.045						
110	.019	.024	.034	.053						
115	.021	.027	.039	.063						
120	.022	.030	.045							
125	.024	.034	.053							
130	.027	.039	.063							
135	.030	.045								
140	.034	.053								
145	.039	.063								
150	.045									
155	.053									
160	.063									

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	**40**
Missile, Launch	**40**

Π_C **(Complexity Factor)**

Complexity	Π_C
Single Transistor	1.0
Dual (Unmatched)	0.7
Dual (Matched)	1.2
Darlington	0.8
Dual Emitter	1.1
Multiple Emitter	1.2
Complementary Pair	0.7

Π_{S2} **(Voltage Stress Factor)**

S_2 (percent)	Π_{S_2}
100	3.0
90	2.25
80	1.65
70	1.2
60	1.0
50	0.75
40	0.48
30	0.36
20	0.30
10	0.30
0	0.30

Π_A **Application Factor)**

Application	Π_A
Linear	1.5
Logic Switch	0.7
High Frequency (R.F. >400 MHz)	5.0

Π_Q **(Quality Factor)**

Quality Level	Π_Q
JANTXV	.2
JANTX	.4
JAN	2.0
Lower	10.0

FIGURE 1.2-3 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR GERMANIUM PNP TRANSISTORS

$$\lambda_p = \lambda_b \; (\pi_E \times \pi_A \times \pi_Q \times \pi_{S2} \times \pi_C) \times 10^{-6}$$

λ_b (Base Failure Rate)

[illegible]	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0031	.0038	.0046	.0056	.0067	.0080	.0095	.011	.013	.017
5	.0035	.0043	.0052	.0063	.0075	.0090	.010	.013	.016	.020
10	.0041	.0049	.0059	.0071	.0084	.010	.012	.015	.018	.025
15	.0046	.0056	.0067	.0080	.0095	.011	.013	.017	.022	.031
20	.0052	.0063	.0075	.0090	.010	.013	.016	.020	.027	.041
25	.0059	.0071	.0084	.010	.012	.015	.018	.025	.035	.056
30	.0067	.0080	.0095	.011	.013	.017	.022	.031	.047	
35	.0075	.0090	.010	.013	.016	.020	.027	.041		
40	.0084	.010	.012	.015	.018	.025	.035	.056		
45	.0095	.011	.013	.017	.022	.031	.047			
50	.010	.013	.016	.020	.027	.041				
55	.012	.015	.018	.025	.035	.056				
60	.013	.017	.022	.031	.047					
65	.016	.020	.027	.041						
70	.018	.025	.035	.056						
75	.022	.031	.047							
80	.027	.041								
85	.035	.056								
90	.047									

π_E (Environmental Factor)

Environment	π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

π_C (Complexity Factor)

Complexity	π_C
Single Transistor	1.0
Dual (Unmatched)	0.7
Dual (Matched)	1.2
Darlington	0.8
Dual Emitter	1.1
Multiple Emitter	1.2
Complementary Pair	0.7

π_{S2} (Voltage Stress Factor)

S_2 (percent)	π_{S_2}
100	3.0
90	2.25
80	1.65
70	1.2
60	1.0
50	0.75
40	0.48
30	0.36
20	0.30
10	0.30
0	0.30

π_A (Application Factor)

Application	π_A
Linear	1.5
Logic Switch	0.7
High Frequency (R.F. >400 MHz)	5.0

π_Q (Quality Factor)

Quality Level	π_Q
JANTXV	.2
JANTX	.4
JAN	2.0
Lower	10.0

FIGURE 3.2-4 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR GERMANIUM NPN TRANSISTORS

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_{S2} \times \Pi_C \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0076	.0094	.011	.014	.016	.020	.024	.029	.036	.046
5	.0088	.010	.013	.015	.019	.023	.028	.034	.042	.055
10	.010	.012	.014	.018	.021	.026	.032	.039	.050	.067
15	.011	.014	.016	.020	.024	.029	.036	.046	.060	.083
20	.013	.015	.019	.023	.028	.034	.042	.055	.074	.10
25	.014	.018	.021	.026	.032	.039	.050	.067	.095	.14
30	.016	.020	.024	.029	.036	.046	.060	.083	.12	
35	.019	.023	.028	.034	.042	.055	.074	.10		
40	.021	.026	.032	.039	.050	.067	.095	.14		
45	.024	.029	.036	.046	.060	.083	.12			
50	.028	.034	.042	.055	.074	.10				
55	.032	.039	.050	.067	.095	.14				
60	.036	.046	.060	.083	.12					
65	.042	.055	.074	.10						
70	.050	.067	.095	.14						
75	.060	.083	.12							
80	.074	.10								
85	.095	.14								
90	.12									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_C (Complexity Factor)

Complexity	Π_C
Single Transistor	1.0
Dual (Unmatched)	0.7
Dual (Matched)	1.2
Darlington	0.8
Dual Emitter	1.1
Multiple Emitter	1.2
Complementary Pair	0.7

Π_{S2} (Voltage Stress Factor)

S_2 (percent)	Π_{S_2}
100	3.0
90	2.25
80	1.65
70	1.2
60	1.0
50	0.75
40	0.48
30	0.36
20	0.30
10	0.30
0	0.30

Π_A (Application Factor)

Application	Π_A
Linear	1.5
Logic Switch	0.7
High Frequency (R.F. >400 MHz)	5.0

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	.2
JANTX	.4
JAN	2.0
Lower	10.0

FIGURE 3.2-5 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR FIELD EFFECT TRANSISTORS

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_C) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0092	.011	.013	.016	.019	.022	.026	.031	.039	.052
10	.010	.012	.015	.018	.021	.024	.029	.036	.047	.065
20	.012	.014	.017	.020	.023	.028	.034	.043	.058	.088
25	.012	.015	.018	.021	.024	.029	.036	.047	.066	.10
30	.013	.016	.019	.022	.026	.031	.039	.052	.076	
40	.015	.018	.021	.024	.029	.036	.047	.066	.10	
50	.017	.020	.023	.028	.034	.043	.058	.088		
55	.018	.021	.024	.029	.036	.047	.066	.10		
60	.019	.022	.026	.031	.039	.052	.076			
65	.020	.023	.028	.034	.043	.058	.088			
70	.021	.024	.029	.036	.047	.066	.10			
75	.022	.026	.031	.039	.052	.076				
80	.023	.028	.034	.043	.058	.088				
85	.024	.029	.036	.047	.066	.10				
90	.026	.031	.039	.052	.076					
95	.028	.034	.043	.058	.088					
100	.029	.036	.047	.066	.10					
105	.031	.039	.052	.076						
110	.034	.043	.058	.088						
115	.036	.047	.066	.10						
120	.039	.052	.076							
125	.043	.058	.088							
130	.047	.066	.10							
135	.052	.076								
140	.058	.088								
145	.066	.10								
150	.076									
155	.088									
160	.10									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_C (Complexity Factor)

Complexity	Π_C
Single Device	1.0
Dual (Unmatched)	0.7
Dual (Matched)	1.2
Dual Complementary	0.7
Tetrode	1.1

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	.2
JANTX	.4
JAN	2.0
Lower	10.0

Π_A (Application Factor)

Application	Π_A
Linear	1.5
Logic Switch	0.7
High Frequency (R.F. >400 MHz)	5.0

FIGURE 3.2-6 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR UNIJUNCTION TRANSISTORS

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0064	.0088	.011	.015	.019	.024	.031	.039	.052	.073
10	.0079	.010	.013	.017	.022	.028	.036	.047	.064	.095
20	.0097	.012	.016	.020	.026	.033	.043	.058	.083	.13
25	.010	.013	.017	.022	.028	.036	.047	.064	.095	.15
30	.011	.015	.019	.024	.031	.039	.052	.073	.11	
40	.013	.017	.022	.028	.036	.047	.064	.095	.15	
50	.016	.020	.026	.033	.043	.058	.083	.13		
55	.017	.022	.028	.036	.047	.064	.095	.15		
60	.019	.024	.031	.039	.052	.073	.11			
65	.020	.026	.033	.043	.058	.083	.13			
70	.022	.028	.036	.047	.064	.095	.15			
75	.024	.031	.039	.052	.073	.11				
80	.026	.033	.043	.058	.083	.13				
85	.028	.036	.047	.064	.095	.15				
90	.031	.039	.052	.073	.11					
95	.033	.043	.058	.083	.13					
100	.036	.047	.064	.095	.15					
105	.039	.052	.073	.11						
110	.043	.058	.083	.13						
115	.047	.064	.095	.15						
120	.052	.073	.11							
125	.058	.083	.13							
130	.064	.095	.15							
135	.073	.11								
140	.083	.13								
145	.095	.15								
150	.11									
155	.13									
160	.15									

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_Q **(Quality Factor)**

Quality Level	Π_Q
JANTXV	.8
JANTX	1.6
JAN	8.0
Lower	40.0

FIGURE 3.2-7 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR SILICON (GENERAL PURPOSE) DIODES

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_{S2} \times \Pi_C) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0005	.0007	.0010	.0014	.0019	.0025	.0033	.0043	.0057	.0082
10	.0006	.0009	.0013	.0017	.0023	.0030	.0039	.0052	.0072	.011
20	.0008	.0012	.0016	.0021	.0027	.0036	.0047	.0064	.0095	.016
25	.0009	.0013	.0017	.0023	.0030	.0039	.0052	.0072	.011	.020
30	.0010	.0014	.0019	.0025	.0033	.0043	.0057	.0082	.013	
40	.0013	.0017	.0023	.0030	.0039	.0052	.0072	.011	.020	
50	.0016	.0021	.0027	.0036	.0047	.0064	.0095	.016		
55	.0017	.0023	.0030	.0039	.0052	.0072	.011	.020		
60	.0019	.0025	.0033	.0043	.0057	.0082	.013			
65	.0021	.0027	.0036	.0047	.0064	.0095	.016			
70	.0023	.0030	.0039	.0052	.0072	.011	.020			
75	.0025	.0033	.0043	.0057	.0082	.013				
80	.0027	.0036	.0047	.0064	.0095	.016				
85	.0030	.0039	.0052	.0072	.011	.020				
90	.0033	.0043	.0057	.0082	.013					
95	.0036	.0047	.0064	.0095	.016					
100	.0039	.0052	.0072	.011	.020					
105	.0043	.0057	.0082	.013						
110	.0047	.0064	.0095	.016						
115	.0052	.0072	.011	.020						
120	.0057	.0082	.013							
125	.0064	.0096	.016							
130	.0072	.011	.020							
135	.0082	.013								
140	.0095	.016								
145	.011	.020								
150	.013									
155	.016									
160	.020									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_A (Application Factor)

Application	Π_A
Small Signal ($\leq$500ma)	1.0
Logic Switching	0.6
Power Rectifier (>500ma)	1.5
Power Rectifier (H.V. Stacks) V_{max} >600	2.5/junct

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	.5
JANTX	1.0
JAN	5.0
Lower	25.0

Π_{S2} (Voltage Stress Factor)

S_2 (percent)	Π_{S_2}
0 to 60	0.70
70	0.75
80	0.80
90	0.90
100	1.0

Π_C (Construction Factor)

Contact Construction	Π_C
Metallurgically Bonded	1
Non-Metallurgically Bonded (Spring loaded contacts)	2

FIGURE 3.2-8 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR GERMANIUM (GENERAL PURPOSE) DIODES

$$\lambda_p = \lambda_b \; (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_{S2} \times \Pi_C) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0003	.0005	.0007	.0009	.0013	.0017	.0022	.0030	.0040	.0054
5	.0004	.0006	.0008	.0011	.0015	.0020	.0027	.0036	.0049	.0068
10	.0005	.0008	.0010	.0014	.0019	.0025	.0033	.0044	.0061	.0087
15	.0007	.0009	.0013	.0017	.0022	.0030	.0040	.0054	.0077	.011
20	.0008	.0011	.0015	.0020	.0027	.0036	.0049	.0068	.010	.016
25	.0010	.0014	.0019	.0025	.0033	.0044	.0061	.0087	.013	.024
30	.0013	.0017	.0022	.0030	.0040	.0054	.0077	.011	.019	
35	.0015	.0020	.0027	.0036	.0049	.0068	.010	.016		
40	.0019	.0025	.0033	.0044	.0061	.0087	.013	.024		
45	.0022	.0030	.0040	.0054	.0077	.011	.019			
50	.0027	.0036	.0049	.0068	.010	.016				
55	.0033	.0044	.0061	.0087	.013	.024				
60	.0040	.0054	.0077	.011	.019					
65	.0049	.0068	.010	.016						
70	.0061	.0087	.013	.024						
75	.0077	.011	.019							
80	.010	.016								
85	.013	.024								
90	.019									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_A (Application Factor)

Application	Π_A
Small Signal (≤500ma)	1.0
Logic Switching	0.6
Power Rectifier (>500ma)	1.5
Power Rectifier (H.V. Stacks) V_{max} >600	2.5/junct

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	.5
JANTX	1.0
JAN	5.0
Lower	25.0

Π_{S2} (Voltage Stress Factor)

S_2 (percent)	Π_{S_2}
0 to 60	0.70
70	0.75
80	0.80
90	0.90
100	1.0

Π_C (Construction Factor)

Contact Construction	Π_C
Metallurgically Bonded	1
Non-Metallurgically Bonded (Spring loaded contacts)	2

FIGURE 3.2-9 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR ZENER AND AVALANCHE DIODES

$$\lambda_p = \lambda_b \ (\Pi_E \ X \ \Pi_A \ X \ \Pi_Q \ ) \ X \ 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0024	.0028	.0032	.0036	.0041	.0052	.0061	.0073	.0094	
10	.0027	.0031	.0035	.0039	.0044	.0050	.0058	.0068	.0086	.011
20	.0029	.0033	.0038	.0042	.0048	.0055	.0064	.0079	.010	.015
25	.0031	.0035	.0039	.0044	.0050	.0058	.0068	.0086	.011	.018
30	.0032	.0036	.0041	.0046	.0052	.0061	.0073	.0094	.013	
40	.0035	.0039	.0044	.0050	.0058	.0068	.0086	.011	.018	
50	.0038	.0042	.0048	.0055	.0064	.0079	.010	.015		
55	.0039	.0044	.0050	.0058	.0068	.0086	.011	.018		
60	.0041	.0046	.0052	.0061	.0073	.0094	.013			
65	.0042	.0048	.0055	.0064	.0079	.010	.015			
70	.0044	.0050	.0058	.0068	.0086	.011	.018			
75	.0046	.0052	.0061	.0073	.0094	.013				
80	.0048	.0055	.0064	.0079	.010	.015				
85	.0050	.0058	.0068	.0086	.011	.018				
90	.0052	.0061	.0073	.0094	.013					
95	.0055	.0064	.0079	.010	.015					
100	.0058	.0068	.0086	.011	.018					
105	.0061	.0073	.0094	.013						
110	.0064	.0079	.010	.015						
115	.0068	.0086	.011	.018						
120	.0073	.0094	.013							
125	.0079	.010	.015							
130	.0086	.011	.018							
135	.0094	.013								
140	.010	.015								
145	.011	.018								
150	.013									
155	.015									
160	.018									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_A (Application Factor)

Application	Π_A
Voltage Regulator	1.0
Voltage Reference (Temp. Compensated)	1.5

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	.5
JANTX	1.0
JAN	5.0
Lower	25.0

FIGURE 3.2-10 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR THYRISTORS

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Stress Ratio .1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0006	.0009	.0013	.0018	.0024	.0033	.0044	.0059	.0081	.011
10	.0008	.0012	.0016	.0022	.0030	.0039	.0053	.0072	.010	.014
20	.0010	.0015	.0020	.0027	.0036	.0048	.0065	.0090	.012	.019
25	.0012	.0016	.0022	.0030	.0039	.0053	.0072	.010	.014	.022
30	.0013	.0018	.0024	.0033	.0044	.0059	.0081	.011	.017	
40	.0016	.0022	.0030	.0039	.0053	.0072	.010	.014	.022	
50	.0020	.0027	.0036	.0048	.0065	.0090	.012	.019		
55	.0022	.0030	.0039	.0053	.0072	.010	.014	.022		
60	.0024	.0033	.0044	.0059	.0081	.011	.017			
65	.0027	.0036	.0048	.0065	.0090	.012	.019			
70	.0030	.0039	.0053	.0072	.010	.014	.022			
75	.0033	.0044	.0059	.0081	.011	.017				
80	.0036	.0048	.0065	.0090	.012	.019				
85	.0039	.0053	.0072	.010	.014	.022				
90	.0044	.0059	.0081	.011	.017					
95	.0048	.0065	.0090	.012	.019					
100	.0053	.0072	.010	.014	.022					
105	.0059	.0081	.011	.017						
110	.0065	.0090	.012	.019						
115	.0072	.010	.014	.022						
120	.0081	.011	.017							
125	.0090	.012	.019							
130	.010	.014	.022							
135	.011	.017								
140	.012	.019								
145	.014	.022								
150	.017									
155	.019									
160	.022									

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	40
Missile, Launch	40

Π_Q **(Quality Factor)**

Quality Level	Π_Q
JANTXV	.5
JANTX	1.0
JAN	5.0
Lower	25.0

FIGURE 3.2-11 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR SILICON MICROWAVE DETECTORS

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.035	.037	.039	.042	.044	.047	.050	.055	.062	.075
5	.036	.038	.040	.042	.045	.048	.052	.057	.066	.082
10	.037	.039	.041	.043	.046	.049	.054	.060	.072	.092
15	.038	.040	.042	.044	.047	.051	.056	.064	.078	.10
20	.038	.041	.043	.046	.049	.053	.059	.069	.087	.12
25	.039	.042	.044	.047	.050	.055	.062	.075	.098	.15
30	.040	.042	.045	.048	.052	.057	.066	.082	.11	
35	.041	.043	.046	.049	.054	.060	.072	.092	.13	
40	.042	.044	.047	.051	.056	.064	.078	.10		
45	.043	.046	.049	.053	.059	.069	.087	.12		
50	.044	.047	.050	.055	.062	.075	.098	.15		
55	.045	.048	.052	.057	.066	.082	.11			
60	.046	.049	.054	.060	.072	.092	.13			
65	.047	.051	.056	.064	.078	.10				
70	.049	.053	.059	.069	.087	.12				
75	.050	.055	.062	.075	.098	.15				
80	.052	.057	.066	.082	.11					
85	.054	.060	.072	.092	.13					
90	.056	.064	.078	.10						
95	.059	.069	.087	.12						
100	.062	.075	.098	.15						
105	.066	.082	.11							
110	.072	.092	.13							
115	.078	.10								
120	.087	.12								
125	.098	.15								
130	.11									
135	.13									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	10
Airborne, Inhabited	50
Naval, Sheltered	50
Ground, Mobile	50
Naval, Unsheltered	50
Airborne, Uninhab.	80
Missile, Launch	200

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	1.0
JANTX	2.0
JAN	3.5
Lower	5.0

FIGURE 3.2-12 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR GERMANIUM MICROWAVE DETECTORS

$$\lambda_p = \lambda_b \; (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.061	.063	.066	.069	.072	.076	.080	.085	.092	.10
5	.064	.066	.069	.072	.076	.081	.086	.092	.10	.11
10	.066	.069	.073	.077	.081	.087	.093	.10	.11	.12
15	.070	.073	.077	.082	.087	.094	.10	.11	.12	.14
20	.074	.078	.082	.088	.095	.10	.11	.13	.15	.17
25	.078	.083	.089	.096	.10	.11	.13	.15	.18	.22
30	.083	.089	.097	.10	.11	.13	.15	.18	.22	
35	.090	.098	.10	.12	.13	.15	.18	.23		
40	.099	.10	.12	.13	.16	.19	.24			
45	.11	.12	.14	.16	.19	.24				
50	.12	.14	.16	.20						
55	.14	.17	.20							
60	.17	.21								
65	.21									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	10
Airborne, Inhabited	50
Naval, Sheltered	50
Ground, Mobile	50
Naval, Unsheltered	50
Airborne, Uninhab.	80
Missile, Launch	200

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	1.0
JANTX	2.0
JAN	3.5
Lower	5.0

FIGURE 3.2-13 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR SILICON MICROWAVE MIXERS

$$\lambda_p = \lambda_b\ (\Pi_E \times \Pi_Q)\ \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.047	.050	.053	.056	.060	.064	.069	.076	.086	.10
5	.049	.052	.055	.058	.061	.066	.071	.079	.092	.11
10	.050	.053	.056	.059	.063	.068	.074	.083	.099	.12
15	.051	.054	.057	.061	.065	.070	.077	.089	.10	.14
20	.052	.055	.058	.062	.067	.072	.081	.095	.12	.16
25	.053	.056	.060	.064	.069	.076	.086	.10	.13	.20
30	.055	.058	.061	.066	.071	.079	.092	.11	.15	
35	.056	.059	.063	.068	.074	.083	.099	.12	.18	
40	.057	.061	.065	.070	.077	.089	.10	.14		
45	.058	.062	.067	.072	.081	.095	.12	.16		
50	.060	.064	.069	.076	.086	.10	.13	.20		
55	.061	.066	.071	.079	.092	.11	.15			
60	.063	.068	.074	.083	.099	.12	.18			
65	.065	.070	.077	.089	.10	.14				
70	.067	.072	.081	.095	.12	.16				
75	.069	.076	.086	.10	.13	.20				
80	.071	.079	.092	.11	.15					
85	.074	.083	.099	.12	.18					
90	.077	.089	.10	.14						
95	.081	.095	.12	.16						
100	.086	.10	.13	.20						
105	.092	.11	.15							
110	.099	.12	.18							
115	.10	.14								
120	.12	.16								
125	.13	.20								
130	.15									
135	.18									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	10
Airborne, Inhabited	50
Naval, Sheltered	50
Ground, Mobile	50
Naval, Unsheltered	50
Airborne, Uninhab.	80
Missile, Launch	200

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	1.0
JANTX	2.0
JAN	3.5
Lower	5.0

FIGURE 3.2-14 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR GERMANIUM MICROWAVE MIXERS

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.10	.10	.11	.11	.12	.12	.13	.14	.15	.16
5	.10	.11	.11	.12	.13	.13	.14	.15	.17	.18
10	.11	.11	.12	.13	.13	.14	.15	.17	.19	.21
15	.11	.12	.13	.13	.14	.16	.17	.19	.21	.25
20	.12	.13	.14	.15	.16	.17	.19	.22	.25	.30
25	.13	.14	.15	.16	.17	.19	.22	.25	.30	.37
30	.14	.15	.16	.18	.20	.22	.26	.31	.38	
35	.15	.16	.18	.20	.23	.16	.32	.39		
40	.16	.18	.20	.23	.27	.32				
45	.18	.20	.23	.27	.33					
50	.21	.24	.28	.34						
55	.24	.29	.35							
60	.29	.36								
65	.36									

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	10
Airborne, Inhabited	50
Naval, Sheltered	50
Ground, Mobile	50
Naval, Unsheltered	50
Airborne, Uninhab.	80
Missile, Launch	200

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTXV	1.0
JANTX	2.0
JAN	3.5
Lower	5.0

FIGURE 3.2-15 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR VARACTORS, STEP RECOVERY & TUNNEL DIODES

$$\lambda_p = \lambda_b \; (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T	Stress Ratio									
(°C)	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.016	.020	.024	.028	.034	.040	.047	.056	.070	.093
10	.018	.022	.027	.032	.037	.044	.053	.065	.084	.11
20	.021	.025	.030	.035	.042	.050	.061	.077	.10	.15
25	.022	.027	.032	.037	.044	.053	.065	.084	.11	.18
30	.024	.028	.034	.040	.047	.056	.070	.093	.13	
40	.027	.032	.037	.044	.053	.065	.084	.11	.18	
50	.030	.035	.042	.050	.061	.077	.10	.15		
55	.032	.037	.044	.053	.065	.084	.11	.18		
60	.034	.040	.047	.056	.070	.093	.13			
65	.035	.042	.050	.061	.077	.10	.15			
70	.037	.044	.053	.065	.084	.11	.18			
75	.040	.047	.056	.070	.093	.13				
80	.042	.050	.061	.077	.10	.15				
85	.044	.053	.065	.084	.11	.18				
90	.047	.056	.070	.093	.13					
95	.050	.061	.077	.10	.15					
100	.053	.065	.084	.11	.18					
105	.056	.070	.093	.13						
110	.061	.077	.10	.15						
115	.065	,084	.11	.18						
120	.070	.093	.13							
125	.077	.10	.15							
130	.084	.11	.18							
135	.093	.13								
140	.10	.15								
145	.11	.18								
150	.13									
155	.15									
160	.18									

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	5
Airborne, Inhabited	25
Naval, Sheltered	25
Ground, Mobile	25
Naval, Unsheltered	25
Airborne, Uninhab.	**40**
Missile, Launch	**40**

Π_Q **(Quality Factor)**

Quality Level	Π_Q
JANTXV	.5
JANTX	1.0
JAN	5.0
Lower	25.0

3.2.3 Instructions for Use of Semiconductor Models

3.2.3.1 Device Power Ratings

Semiconductor base failure rates, λ_b, are commonly related to the junction temperature. This junction temperature consists of the heat rise within the device caused by power dissipated in the junction plus the case temperature. In turn, the case temperature is related to the ambient air or to the attached heat sink temperature.

Transistors are normally rated at maximum power dissipation and diodes at maximum current permissible. Certain special-purpose devices are rated at artificial maximum ratings many times higher than normal operating conditions and at rating values which are based on burn-out of the device (e.g., Microwave Mixers).

Some maximum ratings are based on operation at a 25 degree C ambient temperature and others on a 25 degree C case temperature (the latter primarily for power devices used on heat sinks). Usually this double-type of rating is trouble-free as long as the device is used according to the type of rating.

Usually each device is given two rating points. One for maximum permissible junction temperature and the other for the maximum case or ambient temperature at which 100 percent of the rated load can be dissipated without causing the sum of ambient or case plus internal temperature rise to exceed the specified maximum junction temperature (derating point, T_S). As the ambient or case temperature rises above T_S value, the internal temperature rise and power load must be decreased if the combined temperature is not to exceed the maximum junction temperature. See Figure 3.2-16.

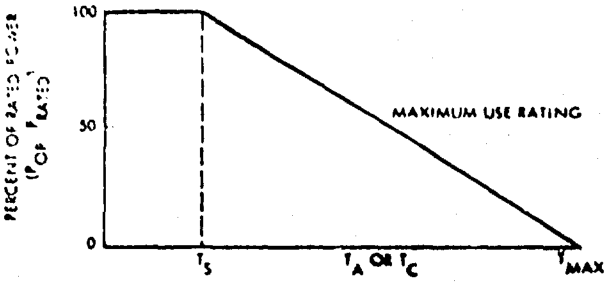


FIGURE 3.2-16 CONVENTIONAL DERATING CURVE

where:

T_S is the temperature derating point (degrees C)

T_{MAX} is maximum junction temperature (degrees C)

T_A is ambient temperature (degrees C)

T_C is case temperature (degrees C)

Maximum junction temperature (T_{MAX}) is normally 175 degrees C for silicon and 100 degrees C for germanium devices. Usually 25 degrees C, T_S can be other values of temperature.

Some devices have a multi-point derating curve as shown by the solid line in the example of Figure 3.2-17. The failure rate of a device with multi-point derating can be estimated with the present models by assuming the device to be linearly derated from T_S to T_{MAX} as shown by the dashed line. The use of this assumption will result in a predicted failure rate higher than what the device might actually experience, with the amount of error dependent upon the difference between the two rating values where T_S, intersects the assumed and actual rating plots.

Since semiconductors may be rated based upon ambient or case temperatures, the following guidance is included:

1) When determining failure rate for a device with rating based upon ambient temperature and is used without a heat sink, calculate S per Section 3.2.3.2. Enter base failure rate table with actual operating ambient temperature or a corrected temperature if indicated in Section 3.2.3.2.

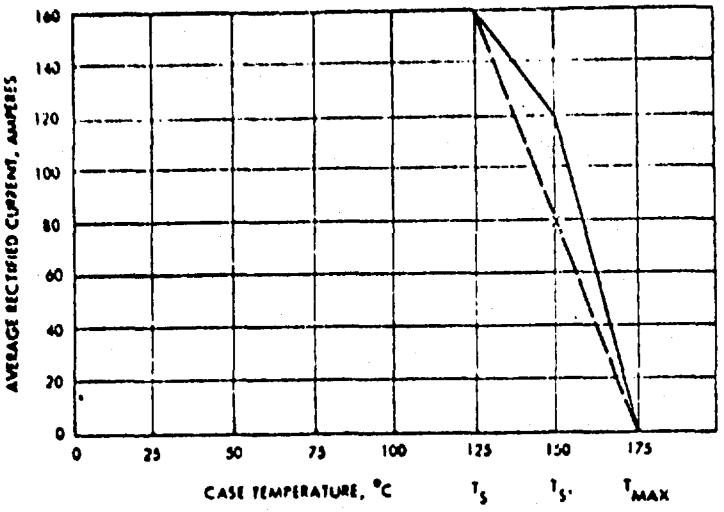


FIGURE 3.2-17 MULTIPOINT DERATING CURVE FOR 1N3263 POWER DIODE

2) When determining the failure rate for a device with rating based on case temperature and is used with a heat sink, calculate S per Section 3.2.3.2. Enter base failure rate table with actual operating heat sink temperature or a corrected temperature if indicated in Section 3.2.3.2.

3) When a device has ratings based upon ambient temperature and on case temperature, it can be used with or without a heat sink. If used with a heat sink, proceed as in (2) above. If used without a heat sink, proceed as in (1).

4) When a device is rated based upon ambient temperature and is used with a heat sink, no failure rate can be determined unless the device rating based upon case temperature can be found. If this cannot be determined, calculate the base failure rate as in (2) above.

5) When a device is rated based upon case temperature and is used without a heat sink, no failure rate can be determined unless the device rating based upon ambient temperature can be found. If this cannot be determined, calculate the base failure rate as in (1) and multiply by 10.

3.2.3.2 Determining Appropriate Stress Ratio & Temperature

The base failure rate tables are based upon ambient or case temperature (T degrees C) and electrical stress ratio (S). The following instructions show the methods for calculating S.

In some cases, the operating ambient or case T must be corrected before entering the failure rate tables. These corrections, where needed, are indicated in (7) below. Operating junction temperatures do not have to be calculated to use the models.

1) Groups I, II & III Transistors.

a. Single device in case.

For Silicon, $S = \frac{P_{OP}}{P_{MAX}}$ (C.F.) For Germanium, $S = \frac{P_{OP}}{P_{MAX}}$

where:

P_{OP} = actual power dissipated
P_{MAX}= maximum rated power at T_S
C.F.= stress correction factor per (7) below

b. Dual device in single case (equally rated).

$$S = \left[\frac{P_1}{P_S} + P_2\left(\frac{2P_S - P_T}{P_T \times P_S}\right)\right] \text{(C.F.)}$$

where:

S = stress ratio of side being evaluated
P_1= power dissipation in side being evaluated
P_2= power dissipation in other side of device
P_S= maximum power rating at T_S of one side of the dual device with the other side not operating (one side rating)
P_T= maximum rating at T_S with both sides operating (both side rating)

NOTE: Specifications for dual devices in one case usually give a maximum rating for each device and a total power rating which is significantly less than the sum of individual ratings.

C.F. = stress correction factor per (7) below for silicon
C.F. = 1.0 for germanium

2) Groups IV & VI General Purpose Diodes & Thyristors.

For Silicon, $S = \frac{I_{OP}}{I_{MAX}}$ (C.F.) For Germanium, $S = \frac{I_{OP}}{I_{MAX}}$

where:

I_{OP} = operating average forward current
I_{MAX} = maximum rated average forward current at T_S
C.F. = stress correction factor per (7) below

3) Group V Zener Diodes

Zener diodes are rated for maximum current or power or both. Either rating may be used as follows:

$$S = \frac{P_{OP}}{P_{MAX}} \text{ (C.F.)} \quad \text{or} \quad S = \frac{I_{Z(OP)}}{I_{Z(MAX)}} \text{ (C.F.)}$$

where:

P_{OP} = actual power dissipated
P_{MAX} = maximum rated power at T_S
$I_{Z(OP)}$ = actual operating zener current
$I_{Z(MAX)}$ = maximum rated zener current at T_S
C.F. = stress correction factor per (7) below

4) Group VII Microwave Mixer Diodes

$$S = \frac{\text{Operating Spike Leakage (ergs)}}{\text{Rated Burnout Energy at 25 degrees C}}$$

5) Group VII Microwave Detector Diodes

$$S = \frac{P_{OP} \text{ (Operating Power Dissipation)}}{P_{MAX} \text{ (Rated Power at 25 degrees C)}}$$

6) Group VIII Varactor, Step Recovery, and Tunnel Diodes

$$S = \frac{P_{OP}}{P_{MAX}} \text{ (C.F.)}$$

where:

P_{OP} = operating power dissipated

P_{MAX} = maximum rated power at T_S

C. F.= stress correction factor per (7) below

7) Stress Correction Factor (C.F.)

a. Devices with T_S = 25 degrees C + T_{MAX} = 175 degrees C to 200 degrees C

$$C.F. = 1$$

b. Devices with $T_S \neq$ 25 degrees C + T_{MAX} = 175 degrees C to 200 degrees C

$$C.F. = \frac{175 - T_S}{150}$$

c. Devices with T_S = 25 degrees C + T_{MAX} <175 degrees C

$$C.F. = \frac{T_{MAX} - 25}{150}$$

and enter λ_b table with $T = T_A + (175 - T_{MAX})$

or $T = T_C + (175 - T_{MAX})$

d. Devices with $T_S \neq$ 25 degrees C + T_{MAX} <175 degrees C

$$C.F. = \frac{T_{MAX} - T_S}{150}$$

and enter $\lambda_b$table with $T = T_A + (175 - T_{MAX})$

or $T = T_C + (175 - T_{MAX})$

3.3 Operational/Non-Operational Failure Rate Comparisons

3.3.1 Transistor Operational/Non-Operational Failure Rate Comparisons

Table 3.3-1 presents a comparison of base (ground), missile launch, and storage failure rates and their equivalent K factors for JANTX and JAN devices. The active and non-operational failure rates were calculated for a ground, fixed environment using the models in the previous section. For these calculations the following assumptions were made:

Device:	Linear, Single Transistor
Operating Temp.:	25°C
Stress Ratio:	.5
Voltage Stress:	.75 (50% applied to rated voltage)

The comparison indicates factors of 13 to 63 between operating and non-operating failure rates for JANTX transistors and factors of 11 to 62 between operating and non-operating failure rates for JAN transistors.

The Missile, Launch to Ground, Fixed Operating Ratio is "8" as given by MIL-HDBK-217B.

3.3.2 Diode Operational/Non-Operational Failure Rate Comparisons

A comparison of operational and storage failure rates and the modifying K factors is presented in Table 3.3-2 for JANTX and JAN devices. The ground and missile launch failure rates were calculated using the procedures of MIL-HDBK-217B. The following assumptions were made:

Device:	Metallurgically bonded, Signal
Operating Temp.:	25°C
Stress Ratio:	.5
Voltage Stress:	.5

The comparison indicates factors of 16 to 68 between operating and non-operating failure rates for JANTX diodes and factors of 7 to 71 between operating and non-operating failure rates for JAN diodes.

The Missile, Launch to Ground, Fixed Operating Ratio is "8" as given in MIL-HDBK-217B with the exception of microwave transistors which shows a factor of 20.

TABLE 3.3-1. TRANSISTOR OPERATING AND NON-OPERATING DATA

DEVICE CATEGORY TRANSISTORS	NON-OPERATING FAILURE RATE x 10^{-9}	GROUND, FIXED, OPERATING FAILURE RATE x 10^{-9}	G.F.-OPERATING TO NON-OPERATING RATIO	MISSILE LAUNCH TO G.F.-OPERATING RATIO
JANTX				
Silicon PNP	1.5	20.	13.	8
Silicon NPN	1.5	29.25	20.	8
Germanium NPN	1.5	27.00	18.	8
Germanium PNP	1.5	72.00	48.	8
Field Effect Trans.	1.15	72.00	63.	8
JAN				
Silicon PNP	8.8	100.	11.	8
Silicon NPN	8.8	146.	17.	8
Germanium NPN	8.8	135.	15.	8
Germanium PNP	8.8	375.	43.	8
Field Effect Trans.	5.8	360.	62.	8

TABLE 3.3-2. DIODE OPERATING AND NON-OPERATING FACTORS

DEVICE CATEGORY DIODES	NON-OPERATING FAILURE RATE x 10^{-9}	GROUND, FIXED, OPERATING FAILURE RATE x 10^{-9}	G.F.-OPERATING TO NON-OPERATING RATIO	MISSILE LAUNCH TO G.F.-OPERATING RATIO
<u>JANTX</u>				
Silicon	.48	10.5	22.	8
Germanium	.48	11.5	24.	6
Zener & Avalanche	1.55	25.0	16.	8
Microwave	14.7	1000.0	68.	20
<u>JAN</u>				
Silicon	7.55	52.5	7.	8
Germanium	7.55	57.5	8.	8
Zener & Avalanche	1.55	125.0	81.	8
Microwave	24.5	1750.0	71.	20

4.0 ELECTRONIC VACUUM TUBES

Electronic vacuum tubes are classified into five basic categories: receiver tubes, klystrons, magnetrons, TWT's and gridded tubes.

The magnetron is an oscillator which converts energy extracted from a constant electric field to an RF field. In its most basic configuration, it consists of a cathode, an anode, a set of straps and output couplings. The cathode is a heated cylindrical structure with the emitting surface all around it. The anode is a large block of copper, surrounding the cathode, in which slots and holes are cut. The straps are metal rings connected to alternate segments of the anode block to improve the stability and efficiency of the tube. A coupling loop in one of the cavities extracts the amplified RF energy.

The Klystron is an amplifier characterized by high gain, high power, good efficiency, but relatively narrow bandwidths. It consists of a cathode, a modulating anode, an anode, RF input heater units and electron beam. The modulating anode located close to the cathode provides a means to pulse or modulate the electron beam by varying the applied voltage. The RF cavities serve as the anode since they are at a positive potential with respect to the cathode. Unlike most tubes, electrons are not collected by the anode but rather by the collector located at the far end of the tube. The input and output coupling loops are located in the first and last RF cavities respectively. The focusing magnets provide an axial magnetic field to counteract the mutual repulsion of electrons in the beam thus keeping it collimated.

High power tubes include x-ray radiation shields and a vacion pump to maintain the high vacuum required for proper operation.

The travelling wave tube (TWT) is a thermionic tube characterized by high gain, large bandwidth, reasonable operating voltages but having low efficiency. The TWT is similar to the Klystron in both construction and principle of operation. It contains a cathode, an anode, input and output

RF couplings and focusing magnets. Instead of RF cavities, the TWT contains a "slow wave structure" to accomplish velocity modulation of the beam. In low power tubes, the slow wave structure is a wire helix running axially along the tube. For higher power tubes heavier and more rugged structures capable of dissipating large amounts of heat are required. High power tubes also contain vac-ion pumps to maintain required vacuum.

A special case of the TWT is the Twystron (TWT/Klystron). This is a hybrid tube that essentially consists of a Klystron driving a TWT within a single bottle or enclosure.

The gridded tubes represent a class of grid-controlled tubes. Although capable of large amounts of power, gridded tubes are constrained to the lower frequencies. In general they represent older technology since most modern microwave applications have been taken over by other tubes. Their high frequency constraints limit this application in missiles.

4.1 Storage Reliability Analysis

4.1.1 Failure Mode Analysis

The failure mode analysis is based on a population of over 12,000 tubes, 484 of which failed during storage. Although detailed failure reports were not available on any of the tubes, cause of failure was recorded in most cases. The total number of failures in the population of 12,000 tubes was over 600, however, many of these were system related failures and were not counted as tube failures.

The distribution of tube failures is shown in Figure 4.1-1. The key to the horizontal axis in Figure 4.1-1 is shown in Table 4.1-1. The "%" column represents the percentage of all failures in which a specific mode was observed.

The predominant storage failure mode is gassy, loss of vacuum. This mode represents 38% of all the failures and it was observed three times as many as the second (internal short) most frequent one. When tubes have been in storage without power applied to them, gases either form within the tube or leak in through seals resulting in loss of vacuum. If power is

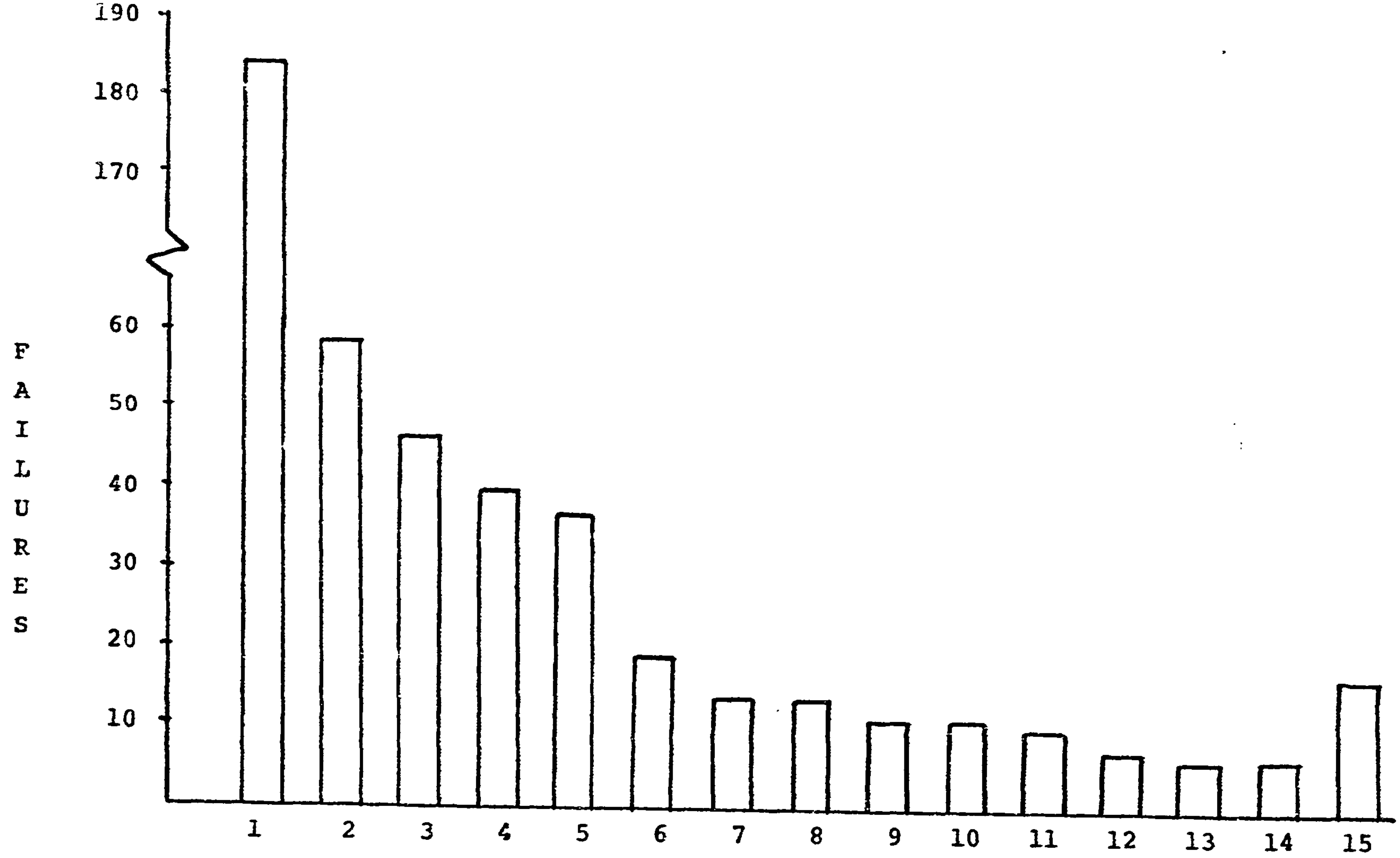


FIGURE 4.1-1. DISTRIBUTION OF FAILURE MODES

TABLE 4.1-1. FAILURE MODE DISTRIBUTION & PERCENTAGE

FAILURE MODE IDENTIFICATION NUMBER	FAILURE MODE	%
1	Gassy, loss of vacuum	38.0
2	Internal short	12.2
3	Undetermined	9.7
4	Open filament	8.3
5	Handling/packaging	7.6
6	Heater short	3.9
7	Tuning mechanism/mechanical failure	2.9
8	Low emission	2.9
9	High gas pressure/high ion pump current	2.3
10	Coolant leak within tube	2.3
11	Internal arcing	2.1
12	Filament failure	1.4
13	Poor spectrum	1.2
14	Cathode depletion	1.2
15	Others	4.0

applied suddenly, the gases ionize and become a conducing media drawing large amounts of current which, if sustained, will burn out the tube. This failure mode was not only predominant in the entire population of tubes but it was also dominant within each tube category except gridded tubes.

Loss of vacuum during prolonged storage is often the result of a microscopic leak in the tube envelope. As the tube skin area and the number of vacuum tight joints increase so does the potential for a leak. In an effort to reduce potential loss of vacuum, the porosity of metals employed should be seriously considered. Small quantities of undesirable gases can also originate from the various metallic surfaces within the vacuum.

Although it was the predominant mode for storage conditions, loss of vacuum is seldom observed during operation. The reason is that while small amounts of gases can leak in while the tube is operating, they are burned as they form and seldom reach high enough concentrations to form arcs.

Internal short was the second highest failure mode. However, over 54% of the failures caused by internal shorts happened in gridded tubes. These were mainly shorts in the delicate grid structure. In tubes other than grid controlled this mode was responsible for only 6% of the failures. Since gridded tubes are not widely used in modern missiles, internal short is not as predominant as shown in Table 4.1-1.

The third most frequent reported mode was "undetermined." These were cases where no failure analysis was made or where it was impossible to determine the actual cause for the failure.

Open filament was reported 8.3% of the time. When combined with heater shorts (3.9%) and undetermined filament failures (1.4%), heater associated failures accounted for 13.6% of the failures. Corrosion and embrittlement of the delicate filament structure with time may account for a large number of these failures.

Handling and packaging accounted for 7.6% of the failures. This is a general category with a wide variety of interpretations the possibilities including dropping a tube resulting in major mechanical damage. Due to the lack of further identification failures attributed to handling and packaging were not included in failure rate computations.

Tuning mechanism failures occurred mostly on mechanically tuned magnetrons. This problem did not occur in TWT's and only a few times in Klystrons. Mechanical tuning is used mostly in high power magnetrons. Small tubes used in missile applications are mostly electronically or voltage tuned. Therefore, this failure mode is not severe in missile environments.

Low emission is usually the predominant operational failure mode. It indicates cathode wearout. As a storage mode it may indicate oxidation of the cathode surface caused by small amounts of moisture trapped within the tube.

The balance of the failures were due to a variety of failure modes none of which represents a major storage associated problem.

4.1.2 NON-OPERATING FAILURE RATE PREDICTION

The failure rate models are presented in Figure 4.1-2. Note, for a number of the tube types, a decreasing failure rate with time is indicated and described by a Weibull model.

4.1.3 NON-OPERATING FAILURE RATE DATA

The failure rate models are based on storage data consisting of over 1.2 billion part hours with 404 failures reported. The breakdown of storage hours and number of failures for each type of tube is shown in Table 4.1-2.

The initial analysis divided the data by types and statistically tested whether the individual entries could be combined into single data sets. Next, the data entries were time lined to attempt to measure the effect of storage time on the failure rate. The analysis indicated a significant decrease in failure rate with storage length for a large majority of the data. This suggested that the devices were failing very early in storage and no significant increase in failure occurred as time increased. An attempt was made to fit the Weibull failure distribution to this data in the form:

$$\lambda(t) = e^{(\beta-1)\mathrm{Ln}t - \mathrm{Ln}\alpha}$$

where $\lambda(t)$ is the hazard rate or instantaneous failure rate per billion hours.

β = shape parameter

α = scale parameter

t = storage hours in billions

A fairly high correlation was made to this function, with the β(shape) parameter less than one, again suggesting that the majority of the failures were occurring early in storage.

As indicated in Table 4.1-2, data was obtained from eight sources. Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or intervals. For vacuum tubes, one

FIGURE 4.1-2.ELECTRONIC VACUUM TUBE NON-OPERATING FAILURE RATE MODELS AND PARAMETERS

TUBE TYPE	FAILURE RATE MODEL	λ_b	α	β
Receiving	$\lambda = \lambda_b$	12	-	-
Klystron, Low Power	$\lambda = \lambda_b$	78	-	-
Klystron, High Power	$\lambda(t) = e^{(\beta-1)\mathrm{Ln}t - \mathrm{Ln}\alpha}$	-	1.0106	0.269
TWT, Low Power & High Power	$\lambda(t) = e^{(\beta-1)\mathrm{Ln}t - \mathrm{Ln}\alpha}$	-	1.0243	0.314
Magnetron, Low Power & High Power	$\lambda(t) = e^{(\beta-1)\mathrm{Ln}t - \mathrm{Ln}\alpha}$	-	1.0467	0.310
Gridded Tubes, Low Power, High Power	$\lambda(t) = e^{(\beta-1)\mathrm{Ln}t - \mathrm{Ln}\alpha}$	-	1.0194	0.254
Amplitrons	$\lambda(t) = e^{(\beta-1)\mathrm{Ln}t - \mathrm{Ln}\alpha}$	-	0.9854	0.214

λ = failures per billion hours

t = storage time in billion hours

TABLE 4.1-2.VACUUM TUBE NON-OPERATING DATA

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
1	A	Sprytron (Hi-Rel)	-	-	-	-	0	.410	<2439.
2		Tubes (MIL-STD)	-	-	-	-	14	1.017	13766.
3	B	TWT	18	-	20	-	0	.266	<3159.
4	F	Magnetron	124	2	7	29	4	.624	6410.
5		TWT	124	2	7	29	1	.624	1663.
6	G	TWT	25	-	18	-	0	.320	3121.
7	Missile E-1	Klystron	874	-	20	-	1	12.760	78.
8		Recng Tubes (JAN)	67298	-	20	-	12	982.552	12.
9	H	Twystron	77	1	27	68	2	1.508	1326.
10		Twystron	12	2	15	26	6	.134	44776.
11		TWT	355	1	11	70	9	2.889	3115.
12		TWT	13	1	9	33	0	.090	<11111.
13		TWT	12	1	12	16	1	.101	9901.
14		Klystron, Pulsed	358	1	37	106	28	9.605	2915.
15		Klystron, Pulsed	103	2	28	99	4	2.089	1915.
16		Klystron, Pulsed	275	1	26	153	18	5.248	3430.
17		Klystron, Pulsed	109	1	20	111	10	1.580	5329.

TABLE 4.1-2. VACUUM TUBE NON-OPERATING DATA (cont'd)

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
18	H	Klystron, Pulsed	102	1	13	99	5	.970	5155.
19		Klystron, Pulsed	452	1	20	116	18	6.576	2737.
20		Klystron, Pulsed	300	1	9	46	7	1.906	3673.
21		Klystron, Pulsed	19	1	12	40	1	.164	6098.
22		Klystron, Pulsed	14	1	79	157	0	.807	<1239.
23		Klystron, CW	29	1	7	24	1	.152	6579.
24		Klystron, CW	253	1	12	85	6	2.138	2806.
25		Klystron, CW	45	1	14	49	4	.467	8565.
26		Klystron, CW	22	5	88	160	2	1.416	1412.
27		Klystron, CW	58	1	7	26	6	.280	21429.
28		Klystron, CW	12	4	18	43	1	.154	6494.
29		Klystron, CW	3	38	61	76	1	.134	7463.
30		Klystron, CW	3	6	19	26	0	.041	<24390.
31		Klystron, CW	130	1	9	104	13	.858	15152.

TABLE 4.1-2.VACUUM TUBE NON-OPERATING DATA (cont'd)

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^6	λ IN FITS
32	H	Klystron, CW	30	1	9	46	0	.196	<5102.
33		Klystron, CW	4	8	22	60	0	.064	<15625.
34		Klystron, CW	2	28	32	35	0	.046	<21739.
35		Klystron, CW	5	1	5	9	0	.018	<55555.
36		Klystron, CW	82	1	15	92	2	.906	2208.
37		Klystron, CW	21	6	88	180	0	1.355	<738.
38		Klystron, CW	54	1	19	83	0	.742	<1348.
39		Klystron, CW	2	11	16	20	0	.023	<43478.
40		Klystron, CW	5	36	60	85	0	.219	<4566.
41		Klystron, CW	71	1	26	103	0	1.341	<746.
42		Klystron, CW	54	1	12	55	3	.465	6452.
43		Klystron, CW	301	1	15	132	9	3.201	2812.
44		Klystron, CW	18	3	20	59	2	.261	7663.
45		Klystron, CW	16	1	25	71	2	.288	6944.

TABLE 4.1-2. VACUUM TUBE NON-OPERATING DATA (cont'd)

DATA ENTRY NO.	SOURCE	TUBE TYPE	NO. OF UNITS	STORAGE INTERVAL (MONTHS) MIN.	AVE.	MAX.	NO. FAILED	STORAGE HRS. x 10^5	λ IN FITS
46	H	Magnetron	2592	1	78	221	116	136.568	849.
47		Magnetron	211	1	23	240	12	3.497	3432.
48		Magnetron	374	1	28	189	13	7.746	1678.
49		Magnetron	261	1	11	74	6	2.144	2799.
50		Magnetron	293	1	10	53	3	2.233	1343.
51		Magnetron	10	3	13	23	1	.091	10989.
52		Magnetron	10	1	10	66	1	.071	14085.
53		Magnetron	244	1	11	53	2	2.011	995.
54		Magnetron	117	1	11	74	2	.969	2064.
55		Magnetron	49	1	12	43	3	.431	6961.
56		Magnetron	9	2	17	66	0	.114	<8772.
57		Gridded Tube	285	1	11	75	10	2.359	4239.
58		Gridded Tube	138	1	13	53	11	1.284	8567.
59		Gridded Tube	356	1	12	78	17	3.119	5450.
60		Amplitron	145	1	19	88	13	1.970	6599.
61	Missile D	Gridded Tube	159	1	17	62	0	1.936	<517.

entry on Sprytron tubes with 400 thousand storage hours and no failures and one entry on MIL-STD tubes with 1 million storage hours and 14 failures were recorded.

Source B represents data from orbiting spacecraft. Eighteen TWT's were in a standby (non-operating) mode and all 18 operated without failure when turned on.

Source F represents missile storage between 1963 and 1965. The missiles were subjected to periodic checkout. Storage intervals ranged from 2 to 29 months. Cumulative operating time on the tubes was from 1 to 20 hours. Four TWT failures were reported with the following failure modes: Moding at start of oscillation (Age - 5 months); Spectrum too wide (Age - 8 months); Arcing (Age - 15 months); and Vibration (Age - 12 months). One magnetron failure was recorded at age 5 months - failure mode - excessive helix current.

Source G represents shelf storage between 1970 and 1972 of large TWT's (peak power - 200 KW). Storage intervals ranged from 6 to 22 months. The devices were conditioned after storage before turn-on. No failures were recorded.

Missile E-1 data represents 874 missiles stored for 20 months during 1967 and 1968. The missiles were stored in containers exposed to external environmental conditions in the northeast U.S. They were also transported from coast to coast. No tests were performed until the end of the 20 months. The data included nearly 13 million klystron storage hours with one failure recorded as "open." In addition, one billion storage hours were recorded for receiving tubes with 13 failures recorded. The failures were listed as defective (3); shorts (5); opens (2); low gain (1), open heaters (2).

Source H represents shelf storage data on high power devices. Table 4-2 lists the tube type and power ratings. Data was not available on which tubes may have been preconditioned upon removal from storage.

Missile D data represents 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes nearly two million storage hours for the triode cavity oscillator with no failures recorded.

Data grouped by age are presented in Tables 4.1-3 through 4.1-8 for each tube type.

A comparison of the low power tube data to the high power tube data was made based on age between the various data sources. For TWT's, Magnetrons and Gridded Tubes, tests indicated no significant difference between the low power and high power tubes.

For the Klystron, the low power tube failure rate was significantly different from the high power tube.

TABLE 4.1-3.TWT (entries 6, 9, 11, 12 & 13) GROUPING OF DATA BY AGE

STORAGE INTERVAL	AVERAGE AGE	UNITS	FAILURES	MILLION HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-2 mo.	1.4 mo.	79	1	.0796	12563	12563
3-5 mo.	3.6 mo.	74	3	.1949	15393	6572
6-9 mo.	7.3 mo.	87	2	.4679	4274	4047
10-17 mo.	13.0 mo.	84	2	.7994	2502	2724
18-24 mo.	19.6 mo.	76	1	1.0877	919	2055
25-70 mo.	38.8 mo.	82	3	2.3229	1291	1286

$$\lambda(t) = e^{(0.314-1)\mathrm{Ln}t - \mathrm{Ln}(1.0243)}$$

Index of Correlation = 0.77

t = Storage time in billion hours

TABLE 4.1-4.TWT (entry 10) GROUPING OF DATA BY AGE

STORAGE INTERVAL	AVERAGE AGE	UNITS	FAILURES	MILLION HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
2-4 mo.	3.0 mo.	3	2	.0066	303030	196742
5-18 mo.	11.7 mo.	3	1	.0256	39063	55265
19-24 mo.	21.3 mo.	3	1	.0467	21413	31452
25-26 mo.	25.3 mo.	3	2	.0555	36036	26755

$$\lambda(t) = e^{(.063-1)\mathrm{Ln}t - \mathrm{Ln}(1.0168)}$$

Index of Correlation = .89

t = storage time in billion hours

STORAGE INTERVAL	AVG. AGE.	UNITS	FAIL-URES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-2 mo.	1.2 mo.	396	15	.4154	36110	23241
3-4 mo.	3.5 mo.	306	12	.7767	15450	12183
5-6 mo.	5.6 mo.	287	12	1.1658	10293	8639
7-8 mo.	7.5 mo.	210	5	1.1154	4483	7101
9-11 mo.	9.9 mo.	255	10	1.8476	5412	5659
12-14 mo.	12.9 mo.	247	8	2.3178	3452	4684
15-19 mo.	16.9 mo.	237	11	2.9229	3763	3836
20-26 mo.	23.[illegible] mo.	252	13	4.2413	3065	3056
27-38 mo.	32.0 mo.	263	23	6.1517	3739	24[illegible]
39-55 mo.	45.7 mo.	249	14	8.3074	1685	1853
56-180 mo.	79.3 mo.	250	20	14.4679	1382	1239

$$\lambda(t) = e^{(.269-1)\text{Ln}t - \text{Ln}(1.0106)}$$

Index of Correlation = 0.90

t = Storage time in billion hours

TABLE 4.1-6. MAGNETRON GROUPINGS BY AGE

STORAGE INTERVAL	AVG. AGE	UNITS	FAILURES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-3 mo.	2.40	305	6	.4373	13721	10284
4-6 mo.	5.2	344	12	1.3052	9194	5256
7-9 mo.	8.1	292	9	1.7286	5207	3866
10-14 mo.	12.0	372	18	3.2040	5618	2985
15-19 mo.	16.9	328	10	4.0354	2478	2334
20-26 mo.	24.0	298	21	5.2136	4028	1831
27-49 mo.	36.1	324	18	8.5468	2106	1379
50-75 mo.	67.9	317	4	15.7645	255	890
76-84 mo.	80.4	320	13	18.7844	692	794
85-92 mo.	88.5	301	5	19.4538	257	743
93-99 mo.	95.8	324	8	22.6475	353	704
100-111 mo.	105.1	330	15	25.3208	592	660
112-240 mo.	127.4	315	20	29.2978	683	578

$$\lambda(t) = e^{(0.310-1)\text{Ln}t - \text{Ln}(1.0467)}$$

Index of Correlation = 0.89

t = Storage time in billion hours

TABLE 4.1-7. GRIDDED TUBES - GROUPING BY AGE

STORAGE INTERVAL	AVG. AGE	UNITS	FAILURES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1	1	87	4	.0635	62992	37384
2	2	62	3	.0905	33149	22283
3	3	63	3	.1380	21739	16463
4-5	4.5	72	1	.2360	4237	12183
6-7	6.5	76	7	.3584	19531	9286
8-9	8.4	70	4	.4271	9365	7662
10-12	11.3	81	5	.6694	7469	6109
13-16	14.5	76	2	.8059	2482	5072
17-22	19.5	70	3	.9965	3011	4071
23-33	27.7	74	3	1.4987	2002	3129
34-78	43.1	47	4	1.4783	2706	2252

$$\lambda(t) = e^{(.254-1)\mathrm{Ln}t - \mathrm{Ln}(1.0194)}$$

Index of Correlation = 0.85

t = Storage time in billion hours

TABLE 4.1-8. AMPLITRON - GROUPING BY AGE

STORAGE INTERVAL	AVG. AGE	UNITS	FAILURES	HOURS	ACTUAL λ IN FITS	PREDICTED λ IN FITS
1-3 mo.	1.9 mo.	26	1	.0321	31153	44703
4-7 mo.	5.5 mo.	24	2	.0964	20747	17690
8-18 mo.	13.4 mo.	23	2	.2256	8865	8769
19-26 mo.	24.2 mo.	23	2	.4073	4910	5512
27-33 mo.	29.4 mo.	27	3	.5789	5182	4743
34-88 mo.	41.3 mo.	22	3	.6628	4526	3630

$$\lambda(t) = e^{(0.214-1)\mathrm{Ln}t - \mathrm{Ln}(.9854)}$$

Index of Correlation = .82

t = Storage time in billion hours

4.2 Electronic Vacuum Tube Operational Prediction Model

The MIL-HDBK-217B failure rate model for electronic vacuum tubes is:

$$\lambda_p = \lambda_b \Pi_E \times 10^{-6}$$

where λ_b = base failure rate in million hours

Π_E = environmental factor

The values for these parameters are shown in Tables 4.2-1 and 4.2-2. The base failure is valid provided tubes are replaced before wearout.

TABLE 4.2-1. BASE FAILURE RATES FOR TUBES

TUBE TYPE	λ_b (f./10^6 hr.)
RECEIVER	
Triode, Tetrode, Pentode	5
Power Rectifier	10
KLYSTRON	
Low Power (e.g., local oscillator)	30
High Power	
VA853	200
VA842	50
L3403	150
L3035	85
SAC42A	110
L3250	110
Z5010	190
ZM2038A	350
If high power type not included above:	
Peak Power <10 Megawatts	200
Peak Power ≥ 10 Megawatts	400
MAGNETRON	
Peak Power <10 Kilowatts	200
Peak Power ≥ 10 Kilowatts	450
TWT	
Peak Power <100 watts	30
Peak Power ≥ 100 watts, $<10,000$ watts	100
Peak Power $\geq 10,000$ watts	200
CROSSED FIELD AMPLIFIER	
QK681	180
TRANSMITTING	
Triode	75
Pentode	100
CRT	15
THYRATRON	50

TABLE 4.2-2. ENVIRONMENTAL FACTOR FOR TUBES

ENVIRONMENT	G_B	S_F	G_F	A_I	N_S	G_M	A_U	N_U	M_L
π_E	0.5	0.5	1.0	6.5	6.5	10	10	10	80

4.3 OPERATIONAL/NON-OPERATIONAL FAILURE RATE COMPARISON

Table 4.3-1 presents a comparison of operational and non-operational failure rates. The non-operational failure rates were calculated based on 10 years storage. The operating failure rates were calculated for a ground-fixed environment.

TABLE 4.3-1. OPERATING TO NON-OPERATING COMPARISON

TUBE TYPE	OPERATING FAILURE RATE (λ_{GF}) IN FITS	NON-OPERATING FAILURE RATE (λ_{NO}) IN FITS	RATIO $\lambda_{GF}/\lambda_{NO}$
Receiving	5000	12	4167.
Klystron, Low Power	30000	78	385.
Klystron, High Power	200000	915	219.
TWT, Low Power	30000	593	51.
TWT, High Power	200000	593	337.
Magnetron, Low Power	200000	602	332.
Magnetron, High Power	450000	602	748.
Gridded Tubes, Low Power	100000	1044	518.
Gridded Tube, High Power	180000	1044	172.

4.4 Conclusions & Recommendations

4.4.1 Conclusions

The primary storage failure mode for most types of high power vacuum tubes is loss of vacuum. Gridded tubes are the exception with the predominant failure mode being internal short.

There is not sufficient evidence to establish a relationship between storage failure rate and power or frequency. In fact, the data tends to indicate independence among those parameters.

There doesn't seem to be a difference in storage failure rate between pulsed and CW tubes. In all cases, pulsed and CW data were combined into a single failure rate.

In some cases, more than one failure rate was found for a particular class of tubes. Different failure rates were quoted when statistical tests indicated the likelihood of different populations within the data. The lack of definition regarding to tube manufacturing, storage conditions, quality grades and conditioning procedures did not permit a complete evaluation of these differences. These are believed to be the results of the combined effects of different manufacturing technologies, quality controls, storage environment, and tube conditioning procedures.

The storage data indicates that vacuum tube failures are occurring early in storage. Therefore, a decreasing failure rate has been predicted. The failure rate models assume that no tests are performed on the tubes in storage. Should the tubes be tested after a year, the failure rate should decrease significantly, since most of the failures should be removed as a result of the test.

Since loss of vacuum is the primary storage failure mode, proper conditioning of power tubes prior to operation would significantly increase the storage reliability.

4.4.2 Recommendations

To avoid gases to be trapped within the tube enclosure during manufacturing, tubes should be assembled in a high vacuum environment. Particular attention should be given to vacuum seals and to the selection of low porosity materials.

During storage, the humidity should be controlled to the maximum extent possible to avoid corrosion of external metal surfaces.

A large number of failures were attributed to handling and packaging. Special attention should be given to the design and construction of containers to avoid damage during transportation and handling.

Tubes equipped with vac-ion pumps should be pumped periodically to insure vacuum. The pump should always be operated prior to installation. Large tubes should be designed with a vac-ion pump.

Prior to full operation the tubes should be conditioned. The process should include as a minimum slow heater warm-up; anode, cathode and helix conditioning by applying high voltage gradually; and RF conditioning by applying RF drive gradually to maximum power level and pulse width.

4.5 References

The data in Section 4 is a summary of the analyses documented in report LC-78-VT1, Storage Reliability of Missile Materiel Program, D. F. Malik, O. L. Soler, Raytheon Co., dated January 1978.

BIBLIOGRAPHY AND REFERENCES

1. "Special Pre-conditioning of PPA-200 Traveling Wave Tubes," General Electric Company, subcontract No. 211-C 22222-3024, Amendment No. 1. Prepared by Raytheon Co. Microwave and Power Tube Div., Waltham, MA, 15 August 1972.
2. "Final Report Post Storage Conditioning Evaluation of 12 PPA-200 TWT's, Contract No. P. O. 211-000465-5-0017, Item 1, Prepared by Raytheon Co., Microwave and Power Tube Div., Waltham, MA, December 20, 1971.
3. Young, K; Hetzel, G. L., "Analysis of Field Reliability Data from Series 600 Missile Borne Guidance Equipment" Technical Memorandum No. 65-6223-3, Bell Telephone Labs, Dec. 15, 1965.
4. Bean, E. E.; Bloomquist, C. E., "Reliability Data from In-Flight Spacecraft, 1958-1970," Document No. PRC-R-1453, PRC Systems Sciences Company, 1100 Glendon Ave., Los Angeles, CA, 90049, 30 Nov. 1971.
5. Bauer, J. A.; Cottrell, D. F.; Gagnier, T. R.; Kimball, E. W.; et al, "Dormancy and Power On-Off Cycling Effects on Electronic Equipment and Part Reliability," RADC-TR-73-248, August 1973.
6. "AIM-7E Storage Reliability," Raytheon Memo 7623-71-322, E. White to B. Reiss, 1 Sept. 1971 (Confidential).
7. "Dormant Failure Rates Update No. 7," Raytheon Memo No. DATA:76:44, C. Lipson to R. J. Krause, 29 Mar. 1976.
8. MIL-HDBK-217B, "Reliability Prediction," dated 20 Sept. 1974.
9. Private correspondence with Frank H. Vogler of Georgia Institute of Technology Engineering Experiment Station, in relation to "High Power Tube Reliability Study" Contract No. F30602-74-C-0229 with FAA and RADC.
10. Brownlee, K. A., "Statistical Theory and Methodology in Science and Engineering," Wiley, 1960, pp. 144-145.
11. LC-78-VT1, "Storage Reliability of Missile Materiel Program, Electronic Vacuum Tube Analysis," D. F. Malik, O. L. Soler, Raytheon Co., January 1978.

5.0 Resistors

Resistors used in electronic equipments are classified in four basic categories: Carbon Composition, Film, Wirewound types, and potentiometers (variable resistors).

The composition resistor (MIL-R-11) consists of a mixture of finely divided carbon and a binder, either in the form of a slug or a heavy coating, on a glass tube. Specially-formed wire leads are embedded in the resistance element. An insulating case, usually phenolic, is molded around the resistor forming a one-piece enclosure to support the leads and provide moisture sealing.

Fixed film resistors usually consist of resistive material, carbon or metal, deposited on the inside or outside of glass or refractory tubes and spirally-cut to achieve specific resistance. Leads in the ends of the tubes and various types of end caps provide connection to the resistance element. As with composition resistors, a molded plastic case provides physical strength and moisture protection.

The two basic types of wirewound resistors covered in this notebook are Precision styles (MIL-R-93) and Power styles (MIL-R-26).

Precision wirewound resistors are formed by winding a special alloy resistance wire on ceramic forms having expansion coefficients matched to that of the wire. By selecting and matching the resistance wire, almost any temperature coefficient of resistance can be obtained. Some types have special low-inductance and segmented windings which achieve good high-frequency response. These resistors are generally well-sealed in molded cases for use in high-humidity atmospheres.

Power wirewound resistors are similar in construction to precision wirewound types but less attention is given to close tolerances and noninductive winding. Greater attention is given to the means of mounting for the extraction of heat. Special silicone coatings are designed for maximum heat conduction and radiation.

Potentiometers used in electronic equipments are classified in five basic categories: Precision, Semi-Precision, Low Precision, Trimmers and Power types with subdivisions according to similar reliability characteristics.

Precision potentiometers (MIL-R-11974, Style RR)are generally wirewound potentiometers on precision coil forms which can be provided in almost any linear or nonlinear resistance configuration.

Semi-Precision Potentiometers, MIL-R-19, Style RA, are also wirewound but with less emphasis on precision and conformity. The bodies and cores of RA Style power potentiometers are constructed of phenolic or other plastic.

Low-Precision Potentiometers, MIL-R-94, Style RV, are generally composition resistor types commonly used for volume or gain control.

Nonwirewound, Trimmer Potentiometers, MIL-R-22097, Style RJ, are in many styles and types of nonwirewound resistance elements.

Wirewound, Trimmer Potentiometers, MIL-R-27208, Style RT, and MIL-R-35015, Style RTR, are similar except for the greater reliability control and burn-in provided for the Established Reliability (RTR) type.

Wirewound, Power Type Potentiometers, MIL-R-22, Style RP, are vitreous and ceramic power units.

5.1 Storage Reliability Analysis

5.1.1 Failure Mechanisms

Most resistors are encapsulated in a molded plastic case or conformally coated to provide moisture protection. But no plastic is the equivalent of hermetic sealing so that moisture is a reliability consideration for all resistors depending on the resistor type. A carbon composition resistor will usually keep itself dry during operation because of its self-generated heat and heat from adjacent components. Long-time storage of carbon composition resistors without operation in a humid atmosphere will result in appreciable increase of resistance. Also, long-time storage in a very dry atmosphere will result in the reverse resistance change. These effects are reduced or eliminated if the composition resistors are potted or hermetically-sealed into higher-order assemblies.

The effect of moisture on film resistors varies according to type. Corrosion or electrolytic action involving impurities or surface contaminants is a major cause of open circuits in the film or between the film and end cap connections. Reduced resistance from this effect prior to final malfunction is frequently hard to detect because of the common localized nature of the effect. Moisture absorbed during storage frequently does not cause serious trouble until after a period of operation with voltage applied to stimulate electrolysis.

Moisture in wirewound resistors is frequently a cause for leakage between turns and between layers which ultimately results in insulation breakdown and shorts. Corrosion and electrolytic action results in open wires or in openings between resistor wire and end cap connections.

Potentiometers cannot be sealed in a complete encapsulated jacket. Even where the resistor element is encased in a plastic or vitreous case there must be a portion of each turn exposed for contact with the wiper arm. This provides many possible points (which can seldom be fully sealed) for the entrance of moisture.

Operator-adjusted potentiometers must have movable shafts which protrude through the case and front panel. This opens the interior of the potentiometer to the environment exterior to protecting cases. Various types of shaft seals such as Elastomer "O" rings are at best imperfect moisture seals.

Interior-mounted trimmer potentiometers are given some shelter and moisture protection by the external case, but even these can seldom be potted or hermetically sealed inside a higher order assembly unit.

Potentiometers have additional failure modes relating to the wiper which are effected by moisture. Precision potentiometers may degrade in linearity or noise as a result of moisture absorption and corrosion.

5.1.2 Non-Operating Failure Rate Predictions

The non-operating failure rates in FITS (failures per billion hours) for various types of resistors are shown in Table 5.1-1.

TABLE 5.1-1 RESISTOR NON-OPERATING FAILURE RATES

TYPE & STYLE	λ IN FITS	90% CONFIDENCE LIMIT λ IN FITS
Composition		
RC	0.22	0.58
RCR	<0.066	0.15
Film		
RN, RL, RDP	0.11	0.42
RNR, RLR, RNC	0.017	0.068
Wire Wound		
RR, RE, RW	1.19	3.16
RBR, RER, RWR	0.20	1.30
Thermistor		
MIL-STD	133.3	296.3
RTH	<16.9	39.1
Variable		
RT, RJ	3.79	10.1
RTR	3.71	9.86
Potentiometer		
RR, RK, RP, RV	<8.40	19.4
Tin Oxide		
Hi Rel	<0.21	0.50

5.1.3 Non-Operating Failure Rate Data

The failure rate table in section 5.1.2 is based on storage data consisting of over 103 billion part hours from several programs, with 14 failures reported. The breakdown of storage hours and number of failures for each type of resistor is shown in Table 5.1-2.

The small number of failures does not allow a detailed analysis of the data.

Data was obtained from eight sources and are listed in Tables 5.1-3 through 5.1-10. Storage details from each source are described below:

Missile D data consists of 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes approximately 4.5 billion resistor storage hours with no failures. All of the devices in missile D are rated Hi Rel.

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included nearly 10.2 billion part hours with four failures reported. All of the devices in missile E-1 are rated MIL-STD.

Missile F data consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southeast desert under open sided metal roof sheds; 30 missiles stored outside in the canal zone under open sided metal roof sheds; and 30 missiles stored in the southeast U. S. in bunkers. The data includes 794 million resistor storage hours with no failures reported.

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. The data includes 389 million resistor storage hours with no failures.

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. The data includes 40 billion resistor storage hours with one failure reported.

Missile I data consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in the U. S. depots while the remainder were stored at various bases around the country. The data includes more than 11 billion resistor storage hours with 1 failure reported.

Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual sources. The data for source A is summarized in Table 5.1-9. Both MIL-STD and HI-REL devices were included.

Source D represents a special testing program on devices stored in an environmentally controlled warehouse for up to 5 years. Approximately 54 million resistor storage hours were reported with no failures.

TABLE 5.1-2 RESISTOR NON-OPERATING DATA SUMMARY

TYPE & STYLE	TOTAL STORAGE HRS. x 10^6	NUMBER OF FAILURES	STYLE	TOTAL STORAGE HRS. x 10^6	NUMBER OF FAILURES	λ IN FITS
Composition						
RC	4478.9	2	RC RCR	9130.9 15064.7	2 0	0.22 (<0.066)
MIL-STD	4652.0	0				
RCR	3867.7	0				
HI REL	11197.0	0				
Film						
RN	5940.9	1	RN, RL, RD/P RNR, RLR,RNC	9236.9 57333.4	1 1	0.11 0.017
MIL-STD	3296.0	0				
RNC	4632.8	0				
RNR	38576.5	0				
RLR	1307.6	0				
HI REL	12816.5	1				
Wirewound, Precision						
MIL-STD	329.0	0	RB, RE, RW RBR, RER, RWR	1674.6 5063.7	2 1	1.19 0.20
RBR	238.1	0				
HI REL	810.3	0				
Wirewound, Power						
RE	1.1	0				
RW	832.5	0				
MIL-STD	376.0	2				
RWR	1261.5	1				
HI REL	2118.7	0				
Wirewound, General						
MIL-STD	136.0	0				
HI REL	635.1	0				

TABLE 5.1-2 RESISTOR NON-OPERATING DATA SUMMARY (continued)

TYPE & STYLE	TOTAL STORAGE HRS. x 10^6	NUMBER OF FAILURES	STYLE	TOTAL STORAGE HRS. x 10^6	NUMBER OF FAILURES	λ IN FITS
Thermistor						
MIL-STD	22.5	3	MIL-STD	22.5	3	133.3
HI-REL	59.1	0	RTH	59.1	0	(<16.9)
Variable, Wirewound						
RT	517.0	1	RT, RJ & MIL-STD Variable	528.1	2	3.79
HI-REL	2.0	0				
Variable, Non WW			RTR & HI-REL Variable	539.2	2	3.71
HI-REL (Trimmer)	370.6	0				
HI-REL (Film)	23.0	1				
HI-REL (Plastic)	1.0	0				
Variable, General						
MIL-STD	11.1	1				
HI-REL	142.6	1				
Potentiometer, Precision Wirewound						
RR	102.1	0				
Potentiometer, Semi-Prec. Wirewound			RR, RK, RP, RV	119.1	0	(<8.40)
RK	17.0	0				
Potentiometer, Power WW						
RP	-	-				
Potentiometer, Low Prec. Composition						
RV	-	-				
Tin Oxide						
HI-REL			HI-REL	4655.0	0	(<0.21)
Network Resistor						
HI-REL			HI-REL	1.1	0	(<909.1)

TABLE 5.1-3. MISSILE D RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Wirewound, Precision	1749	21.3	0	(<46.9)
Wirewound, Power	795	9.7	0	(<103.1)
Composition	353139	4300.0	0	(<0.23)
Film	12084	147.1	0	(<6.80)

TABLE 5.1-4. MISSILE E-1 RESISTOR NON-OPERATING DATA (MIL-STD)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Composition (RC)	306774	4478.9	2	0.45
Film (RN)	366206	5346.6	1	0.19
Wirewound (RW)	18354	268.0	0	(<3.73)
Variable	6992	102.1	1	9.79
Thermal	874	13.0	0	(<76.9)

TABLE 5.1-5. MISSILE F RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Film (RLR)	5400	118.3	0	(<8.45)
Film (RN)	22440	491.4	0	(<2.04)
Composition (RCR)	6480	141.9	0	(<7.05)
Wirewound (RBR)	480	10.5	0	(<95.2)
Wirewound (RW)	720	15.8	0	(<63.3)
Wirewound (RWR)	720	15.8	0	(<63.3)

TABLE 5.1-6. MISSILE G RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Film (RLR)	546	15.7	0	(<63.7)
Film (RN)	3588	102.9	0	(<9.72)
Film (?)	117	3.4	0	(<294.1)
Composition (RCR)	8346	239.3	0	(<4.18)
Wirewound (RBR)	39	1.1	0	(<909.1)
Wirewound (?)	273	7.8	0	(<128.2)
Wirewound (RW)	468	13.4	0	(<74.6)
Wirewound (RE)	39	1.1	0	(<909.1)
Variable Wirewound (RT)	78	2.2	0	(<454.5)
Thermal	39	1.1	0	(<909.1)
Network Resistor	39	1.1	0	(<909.1)

TABLE 5.1-7. MISSILE H RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Film (RNR)	2293011	38576.5	0	(<0.26)
Wirewound (RWR)	77112	1225.1	1	0.82
Thermal	3213	51.0	0	(<19.6)
Variable (RR)	6426	102.1	0	(<9.79)
Variable (RK)	1071	17.0	0	(<58.8)

TABLE 5.1-8. MISSILE I RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Film (RNC)	465750	4632.8	0	(<0.22)
Film (RLR)	117990	1173.6	0	(<0.85)
Wirewound (RW)	53820	535.3	0	(<1.87)
Wirewound (RWR)	2070	20.6	0	(<48.5)
Wirewound (RBR)	22770	226.5	0	(<4.42)
Composition (RCR)	1355850	3486.5	0	(<0.29)
Variable, Non WW	37260	370.6	0	(<27.0)
Variable, Wirewound (RT)	51750	514.8	1	1.94

TABLE 5.1-9. SOURCE A RESISTOR NON-OPERATING DATA

DEVICE TYPE	MIL-STD STORAGE HOURS $\times 10^6$	MIL-STD NUMBER FAILED	MIL-STD FAILURE RATE IN FITS	HI-REL STORAGE HOURS $\times 10^6$	HI-REL NUMBER FAILED	HI-REL FAILURE RATE IN FITS
Carbon Composition	4652.	0	(<.215)	6897.	0	(<.145)
Carbon Film	6.	0	(<166.)	108.	0	(<9.26)
Metal Film	3290.	0	(<.304)	12533.	1	.08
Thermal	-	-	-	2.	0	(<500.)
Thermistor	95.	3	31.6	5.	0	(<200.)
Tin Oxide	-	-	-	4655.	0	(<.215)
Wirewound						
General	136.	0	(<7.35)	602.	0	(<1.66)
Power	376.	2	5.32	2109.	0	(<.474)
Precision	329.	0	3.04	788.	0	(<1.21)
Heater Element	-	-	-	1.	0	(<1000.)
Variable						
General	11.	1	90.9	37.	0	(<27.0)
Film	-	-	-	23.	1	43.5
Plastic	-	-	-	1.	0	(<1000.)
Wirewound	-	-	-	2.	0	(<500.)

TABLE 5.1-10. SOURCE D RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS $\times 10^6$	NUMBER FAILED	FAILURE RATE IN FITS
Film	797	25.0	0	(<39.98)
Wirewound	809	25.3	0	(<39.56)
Variable	111	3.5	0	(<286.7)

5.2 Resistor Operational Prediction Models

The MIL-HDBK-217B general failure rate model for resistors is:

$$\lambda_p = \lambda_b\,(\Pi_E \times \Pi_R \times \Pi_Q) \times 10^{-6}$$

The general model for the variable resistors is as follows:

$$\lambda_p = \lambda_b\,(\Pi_{TAPS} \times \Pi_R \times \Pi_V \times \Pi_C \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

where:

λ_p = device failure rate
λ_b = base failure rate
Π_{TAPS} = Tap Connections Adjustment Factor
Π_R = Resistance Adjustment Factor
Π_V = Voltage Adjustment Factor
Π_C = Construction Class Adjustment Factor
Π_E = Environmental Adjustment Factor
Π_Q = Quality Adjustment Factor

The various types of resistors require different failure rate models that vary to some degree from the basic models. The specific failure rate model and the Π factor values for each type of resistor are presented in figures 5.2-1 through 5.2-14. The base failure rate and adjustment factor values in the figures are based on certain assumptions. See sections 5.2.1 and 5.2.2 for a description of these parameters.

Table 5.2-1 provides a list of resistor generic types with a cross reference to the corresponding figure number of the failure rate model.

5.2.1 Base Failure Rate (λ_b)

The equation for the base failure rate, λ_b, is:

$$\lambda_b = Ae^{B}\left(\frac{T + 273}{N_T}\right)^{G} e\left[\left(\frac{S}{N_s}\right)\left(\frac{T + 273}{273}\right)^{J}\right]^{H}$$

where,

- A is an adjustment factor for each type of resistor to adjust the model to the appropriate failure rate level.
- e is the natural logarithm base, 2.718
- T is the ambient operating temperature (degrees C)
- N_T is a temperature constant
- B is a shaping parameter
- G, H, J are acceleration constants
- N_S is a stress constant
- S is the electrical stress and is the ratio of operating power to rated power

The quantitative values for the base failure rate model factors are given in Tables 5.2-2 and 5.2-3 for the different resistor types.

TABLE 5.2-2

FIXED RESISTOR BASE FAILURE RATE (λ_b) FACTORS

STYLE	MIL-R SPEC.	A	B	N_T	G	N_S	H	J
RB	93	$3(10)^{-3}$	1	398	10	1	1.5	1
RBR	39005	"	"	"	"	"	"	"
RC	11	$4.5(10)^{-9}$	12	343	1	0.6	1	1
RCR	39008	"	12	"	"	"	"	"
RD	11804	0.11	1	551	2.6	1.45	1.3	0.89
RE	18546	$3(10)^{-4}$	2.64	298	1	0.466	1	1
RER	39009	"	"	"	"	"	"	"
RL	22684	$6.5(10)^{-4}$	1	343	3	1	1	1
RLR	39017	"	"	"	"	"	"	"
RN	10509	$1(10)^{-4}$	3.5	398	1	1	1	1
RNR	55182	"	"	"	"	"	"	"
RTH	No. λ_b Model.					See Figure 6.2-8		
RW	26	$5.5(10)^{-4}$	1	298	2	0.5	1	1
RWR	39007	"	"	"	"	"	"	"

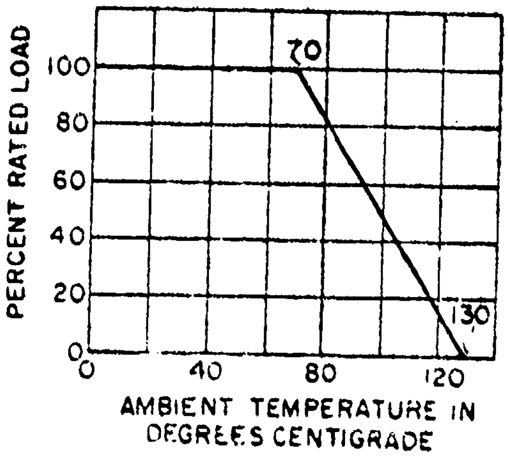
TABLE 5.2-3

VARIABLE RESISTOR BASE FAILURE RATE (λ_b) FACTORS

TYPE	MIL-R SPEC.	A	B	N_T	G	N_S	H	J
RA	19	$3.58(10)^{-2}$	1	355	5.28	1.44	1	4.46
RK	39002	"	"	"	"	"	"	"
RJ	22097	0.423	1	400	7.3	2.69	1	2.46
RP	22	$4.81(10)^{-2}$	1	377	4.66	1.47	1	2.83
RR	12934	$7.35(10)^{-2}$	1	356	4.45	2.74	1	3.51
RT	27208	$6.2(10)^{-3}$	1	358	5	1	1	1
RTR	39015	"	"	"	"	"	"	"
RV	94	$6.16(10)^{-2}$	1	373	9.3	2.32	1	5.3

The ER resistor family generally has four qualification failure rate levels when tested per the requirements of the applicable ER specification. These qualification failure rate levels differ by a factor of ten. However, field data has shown that these failure rate levels differ by a factor about three, hence the Π_Q values have been set accordingly.

The use of the resistor models requires the calculation of the electrical power stress ratio, S = operating power/rated power, or per Section 5.2.3 for variable resistors. The models have been structured such that derating curves do not have to be used to find the base failure rate. The rated power for the S ratio is equal to the full nominal rated power of the resistor. For example, MIL-R-39008 has the following derating curve:



If a 1 watt resistor were being used in an ambient temperature of 90°C, the rated power for the S calculation would still be 1 watt, not 60% of 1 watt. Of course, while the derating curve is not needed to determine the base failure rate, it must still be observed as the maximum operating condition. To aid in determining if a resistor is being used within rated conditions, the base failure rate tables show entries up to certain combinations of stress and temperature. If a given operating stress and temperature point falls in the blank portion of the base failure rate table, the resistor is overrated. Such misapplication would require an analysis of the circuit and operating conditions to bring the resistor within rated conditions.

5.2.2 Π Adjustment Factors

5.2.2.1 Tap Connections Adjustment Factor Π_{TAPS}

Π_{TAPS} accounts for the effect of multiple taps on the resistance element. It is calculated as follows:

$$\Pi_{TAPS} = \frac{(N_{TAPS})^{3/2}}{25} + 0.792$$

where N_{TAPS} is the number of potentiometer taps, including the wiper and end terminations.

5.2.2.2 Resistance Adjustment Factor, Π_R

Π_R adjusts the model for the effect of resistor ohmic values.

5.2.2.3 Voltage Adjustment Factor, Π_V

Π_V adjusts for effect of applied voltage in variable resistors in addition to wattage included in the base failure rate. It is based on the ratio of applied voltage to rated voltage.

The applied voltage is defined as:

$$V \text{ applied} = \sqrt{RP \text{ applied}}$$

where R is the total potentiometer resistance
and P applied is the applied power.

5.2.2.4 Construction Class Adjustment Factor, Π_C

Π_C accounts for influence of construction class of variable resistors as defined in individual part specifications.

5.2.2.5 Environmental Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environments description in the Appendix.

5.2.2.6 Quality Adjustment Factor, Π_Q

Π_Q accounts for effects of different quality. The established reliability resistor family generally has four qualification levels when tested per the requirements of the applicable specification.

RESISTOR OPERATIONAL PREDICTION MODELS CROSS REFERENCE

TYPE	MIL-SPEC	STYLE	FIGURE
Fixed, Composition (Insulated)	MIL-R-39008 MIL-R-11	RCR RC	5.2-1 5.2-1
Fixed, Film (Insulated)	MIL-R-39017 MIL-R-22684	RLR RL	5.2-2 5.2-2
Fixed, Film	MIL-R-55182 MIL-R-10509	RNR RN	5.2-3 5.2-3
Fixed, Film (Power Type)	MIL-R-11804	RD/P	5.2-4
Fixed, Wire Wound (Accurate)	MIL-R-39005 MIL-R-93	RBR RB	5.2-5 5.2-5
Fixed, Wire Wound (Power Type)	MIL-R-39007 MIL-R-26	RWR RW	5.2-6 5.2-6
Fixed, Wire Wound (Power Type) Chassis Mounted	MIL-R-39009 MIL-R-18546	RER RE	5.2-7 5.2-7
Thermistor (Bead and Disk Type)	MIL-T-23648	RTH	5.2-8
Variable, Wire Wound (Lead Screw Actuated)	MIL-R-39015 MIL-R-27208	RTR RT	5.2-9 5.2-9
Variable, Wire Wound, Precision	MIL-R-12934	RR	5.2-10
Variable, Wire Wound, SemiPrecision	MIL-R-19 MIL-R-39002	RA RK	5.2-11 5.2-11
Variable, Wire Wound, Power Type	MIL-R-22	RP	5.2-12
Variable, Non-Wire Wound(Trimmer)	MIL-R-22097	RJ	5.2-13
Variable, Composition, (Low Precision)	MIL-R-94	RV	5.2-14

FIGURE 5.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR INSULATED FIXED COMPOSITION RESISTORS (MIL-R-39008, Style RCR and MIL-R-11, Style RC)

$$\lambda_p = \lambda_b \left(\Pi_R \times \Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.00007	.00009	.0001	.0001	.0001	.0001	.0002	.0002	.0002	.0003
5	.00008	.0001	.0001	.0001	.0001	.0002	.0002	.0002	.0003	.0004
10	.0001	.0001	.0001	.0001	.0002	.0002	.0003	.0003	.0004	.0005
15	.0001	.0001	.0001	.0002	.0002	.0003	.0003	.0004	.0005	.0006
20	.0001	.0001	.0002	.0002	.0003	.0003	.0004	.0005	.0006	.0007
25	.0001	.0002	.0002	.0003	.0003	.0004	.0005	.0006	.0007	.0009
30	.0002	.0002	.0003	.0003	.0004	.0005	.0006	.0007	.0009	.0011
35	.0002	.0003	.0003	.0004	.0005	.0006	.0008	.0009	.0011	.0014
40	.0003	.0003	.0004	.0005	.0006	.0008	.0009	.0011	.0014	.0017
45	.0003	.0004	.0005	.0006	.0008	.0009	.0011	.0014	.0017	.0021
50	.0004	.0005	.0006	.0008	.0009	.0011	.0014	.0017	.0021	.0026
55	.0005	.0006	.0007	.0009	.0011	.0014	.0017	.0021	.0026	.0032
60	.0006	.0007	.0009	.0011	.0014	.0017	.0021	.0026	.0032	.0039
65	.0007	.0009	.0011	.0014	.0017	.0021	.0026	.0032	.0039	.0048
70	.0009	.0011	.0013	.0016	.0020	.0025	.0031	.0039	.0048	.0059
75	.0010	.0013	.0016	.0020	.0025	.0031	.0038	.0047	.0059	
80	.0012	.0015	.0019	.0024	.0030	.0037	.0046	.0058		
85	.0015	.0019	.0023	.0029	.0036	.0045	.0057			
90	.0018	.0022	.0028	.0035	.0044	.0055				
95	.0021	.0027	.0034	.0043	.0054	.0067				
100	.0026	.0032	.0041	.0052	.0065					
105	.0031	.0039	.0049	.0062						
110	.0037	.0047	.0059							
115	.0044	.0056								
120	.0053									
125	.0063									

Π_R (Resistance Factor)

Resistance Range (ohms)	Π_R
Up to 100K	1.0
>.1meg to 1 meg	1.1
>1 meg to 10 meg	1.6
>10 meg	2.5

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	2.0
Airborne, Inhabited	4.0
Naval, Sheltered	5.0
Ground, Mobile	7.0
Naval, Unsheltered	7.5
Airborne, Uninhab.	8.0
Missile, Launch	15.0

Π_Q (Quality Factor)

Failure Rate Level	Π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-11	5.0

FIGURE 5.2-2 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR FIXED FILM (Insulated) RESISTORS (MIL-R-39017, Style RLR and MIL-R-22684, Style RL)

$$\lambda_p = \lambda_b \left(\Pi_R \times \Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Ratio of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0011	.0013	.0014	.0016	.0017	.0019	.0021	.0023	.0026	.0029
5	.0012	.0013	.0015	.0016	.0018	.0020	.0022	.0024	.0027	.0030
10	.0012	.0014	.0015	.0017	.0019	.0021	.0023	.0026	.0028	.0032
15	.0013	.0014	.0016	.0017	.0019	.0022	.0024	.0027	.0030	.0033
20	.0013	.0015	.0016	.0018	.0020	.0023	.0025	.0028	.0031	.0035
25	.0013	.0015	.0017	.0019	.0021	.0024	.0026	.0029	.0033	.0037
30	.0014	.0016	.0018	.0020	.0022	.0025	.0028	.0031	.0035	.0039
35	.0015	.0016	.0018	.0021	.0023	.0026	.0029	.0033	.0037	.0041
40	.0015	.0017	.0019	.0021	.0024	.0027	.0031	.0034	.0038	.0043
45	.0016	.0018	.0020	.0022	.0025	.0029	.0032	.0036	.0041	.0046
50	.0016	.0018	.0021	.0024	.0027	.0030	.0034	.0038	.0043	.0048
55	.0017	.0019	.0022	.0025	.0028	.0032	.0036	.0040	.0045	.0051
60	.0018	.0020	.0023	.0026	.0029	.0033	.0038	.0043	.0048	.0054
65	.0019	.0021	.0024	.0027	.0031	.0035	.0040	.0045	.0051	.0058
70	.0020	.0022	.0025	.0029	.0033	.0037	.0042	.0048	.0054	.0062
75	.0020	.0023	.0027	.0030	.0034	.0039	.0045	.0051	.0058	
80	.0022	.0025	.0028	.0032	.0036	.0041	.0047	.0054	.0061	
85	.0023	.0026	.0030	.0034	.0039	.0044	.0050	.0057		
90	.0024	.0027	.0031	.0036	.0041	.0047	.0053	.0061		
95	.0025	.0029	.0033	.0038	.0043	.0050	.0057			
100	.0026	.0030	.0035	.0040	.0046	.0053	.0061			
105	.0028	.0032	.0037	.0043	.0049	.0056				
110	.0030	.0034	.0039	.0045	.0052	.0060				
115	.0031	.0036	.0042	.0048	.0056					
120	.0033	.0039	.0045	.0052	.0060					
125	.0035	.0041	.0048	.0055						
130	.0038	.0044	.0051	.0059						
135	.0040	.0047	.0054							
140	.0043	.0050	.0058							
145	.0046	.0053								
150	.0049	.0057								

Π_R **(Resistance Factor)**

Resistance Range (ohms)	Π_R
Up to 100K	1.0
>.1meg to 1 meg	1.1
>1 meg to 10 meg	1.6
>10 meg	2.5

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	5.0
Airborne, Inhabited	6.5
Naval, Sheltered	8.0
Ground, Mobile	12.0
Naval, Unsheltered	14.0
Airborne, Uninhab.	15.0
Missile, Launch	35.0

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-22684	5.0

FIGURE 5.2-3 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR FIXED FILM RESISTORS (MIL-R-55182, Style RNR and MIL-R-10509, Style RN)

$$\lambda_p = \lambda_b \; (\Pi_R \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Ratio of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0012	.0013	.0014	.0016	.0018	.0020	.0022	.0024	.0027	.0029
10	.0013	.0014	.0016	.0018	.0020	.0022	.0024	.0027	.0030	.0033
20	.0014	.0016	.0018	.0020	.0022	.0025	.0027	.0031	.0034	.0038
30	.0016	.0017	.0020	.0022	.0025	.0027	.0031	.0034	.0038	.0043
40	.0017	.0019	.0022	.0024	.0027	.0031	.0034	.0039	.0044	.0049
50	.0019	.0021	.0024	.0027	.0030	.0034	.0039	.0044	.0049	.0055
55	.0020	.0022	.0025	.0028	.0032	.0036	.0041	.0046	.0052	.0059
60	.0021	.0023	.0026	.0030	.0034	.0038	.0043	.0049	.0056	.0063
65	.0022	.0025	.0028	.0032	.0036	.0041	.0046	.0052	.0059	.0067
70	.0023	.0026	.0029	.0033	.0038	.0043	.0049	.0055	.0063	.0071
75	.0024	.0027	.0031	.0035	.0040	.0045	.0052	.0059	.0067	.0076
80	.0025	.0028	.0032	.0037	.0042	.0048	.0055	.0062	.0071	.0081
85	.0026	.0030	.0034	.0039	.0044	.0051	.0058	.0066	.0075	.0086
90	.0027	.0031	.0036	.0041	.0047	.0054	.0061	.0070	.0080	.0092
95	.0029	.0033	.0038	.0043	.0049	.0057	.0065	.0074	.0085	.0097
100	.0030	.0034	.0040	.0045	.0052	.0060	.0069	.0079	.0090	.010
105	.0031	.0036	.0042	.0048	.0055	.0063	.0073	.0084	.0096	.011
110	.0033	.0038	.0044	.0050	.0058	.0067	.0077	.0089	.010	.011
115	.0034	.0040	.0046	.0053	.0061	.0071	.0082	.0094	.010	.012
120	.0036	.0042	.0048	.0056	.0065	.0075	.0086	.010	.011	.013
125	.0038	.0044	.0051	.0059	.0068	.0079	.0091	.010	.012	.013
130	.0040	.0046	.0053	.0062	.0072	.0083	.0097	.011	.013	
135	.0041	.0048	.0056	.0065	.0076	.0088	.010	.011	.013	
140	.0043	.0051	.0059	.0069	.0080	.0093	.010	.012		
145	.0046	.0053	.0062	.0072	.0084	.0098	.011	.013		
150	.0048	.0056	.0065	.0076	.0089	.010	.012			
155	.0050	.0058	.0069	.0080	.0094	.011	.012			
160	.0052	.0061	.0072	.0084	.0099	.011	.013			
165	.0055	.0064	.0076	.0089	.010	.012				
170	.0057	.0068	.0080	.0094	.011	.013				
175	.0060	.0071	.0084	.0099	.011	.013				

Π_R **(Resistance Range)**

Resistance Range (ohms)	Π_R
Up to 100K	1.0
>.1meg to 1 meg	1.1
>1 meg to 10 meg	1.6
>10 meg	2.5

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	2.5
Airborne, Inhabited	5.0
Naval, Sheltered	7.5
Ground, Mobile	10.0
Naval, Unsheltered	11.0
Airborne, Uninhab.	12.0
Missile, Launch	18.0

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-10509	1.0

FIGURE 5.2-4 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR POWER FILM RESISTORS (MIL-R-11804, Style RD/P)

$$\lambda_p = \lambda_b \left(\Pi_R \times \Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Ratio of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.141	.148	.157	.168	.180	.194	.210	.229	.249	.273
40	.144	.151	.161	.172	.186	.201	.218	.238	.260	
50	.147	.155	.165	.177	.191	.208	.226	.247	.271	
60	.150	.159	.169	.182	.198	.215	.235	.258		
70	.153	.163	.174	.188	.204	.223	.244	.269		
80	.157	.167	.179	.194	.211	.231	.254			
90	.161	.171	.185	.200	.218	.240	.265			
100	.165	.176	.190	.207	.226	.249				
110	.170	.182	.196	.214	.235	.259				
120	.175	.187	.203	.222	.244					
130	.180	.193	.210	.230	.254					
140	.185	.200	.217	.239						
150	.191	.206	.225	.248						

Π_R **(Resistance Factor)**

Resistance Range (ohms)	Π_R
10 to <100	1.2
100 to <100K	1.0
100K to <1 meg	1.3
>1 meg	3.5

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	5.0
Airborne, Inhabited	6.5
Naval, Sheltered	7.5
Ground, Mobile	12.0
Naval, Unsheltered	13.5
Airborne, Uninhab.	15.0
Missile, Launch	35.0

Π_Q **(Quality Factor)**

Quality Level	Π_Q
Upper	0.4
Mil-Spec	1.0
Lower	3.0

FIGURE 5.2-5 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR FIXED, WIREWOUND (Accurate) RESISTORS (MIL-R-39005, Style RBR and MIL-R-93, Style RB)

$$\lambda_p = \lambda_b \; (\pi_R \times \pi_E \times \pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Ratio of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0032	.0034	.0037	.0040	.0045	.0050	.0056	.0064	.0074	.0086
5	.0032	.0034	.0037	.0041	.0045	.0051	.0058	.0066	.0076	.0089
10	.0033	.0035	.0038	.0041	.0046	.0052	.0059	.0068	.0078	.0092
15	.0033	.0035	.0038	.0042	.0047	.0053	.0060	.0070	.0081	.0095
20	.0033	.0035	.0038	.0043	.0048	.0054	.0062	.0071	.0083	.0098
25	.0033	.0036	.0039	.0043	.0049	.0055	.0063	.0074	.0086	.010
30	.0034	.0036	.0040	.0044	.0050	.0056	.0065	.0076	.0089	.010
35	.0034	.0037	.0040	.0045	.0051	.0058	.0067	.0078	.0093	.011
40	.0035	.0037	.0041	.0046	.0052	.0060	.0069	.0081	.0096	.011
45	.0035	.0038	.0042	.0047	.0053	.0061	.0071	.0084	.010	.012
50	.0036	.0039	.0043	.0048	.0055	.0063	.0074	.0088	.010	.012
55	.0037	.0040	.0044	.0049	.0057	.0066	.0077	.0091	.011	.013
60	.0038	.0041	.0045	.0051	.0059	.0068	.0080	.0096	.011	.014
65	.0039	.0042	.0047	.0053	.0061	.0071	.0084	.010	.012	.014
70	.0040	.0044	.0048	.0055	.0063	.0074	.0088	.010	.012	.015
75	.0042	.0045	.0050	.0057	.0066	.0078	.0093	.011	.013	.016
80	.0043	.0047	.0053	.0060	.0070	.0082	.0099	.011	.014	.018
85	.0045	.0050	.0056	.0064	.0074	.0088	.010	.012	.015	.019
90	.0048	.0052	.0059	.0068	.0079	.0094	.011	.013	.017	.021
95	.0051	.0056	.0063	.0072	.0085	.010	.012	.014	.018	.023
100	.0054	.0060	.0067	.0078	.0091	.010	.013	.016	.020	.025
105	.0059	.0065	.0073	.0085	.010	.012	.014	.018	.022	.028
110	.0064	.0071	.0080	.0093	.011	.013	.016	.020	.025	.032
115	.0071	.0078	.0088	.010	.012	.014	.018	.022	.028	.036
120	.0079	.0087	.0099	.011	.013	.016	.020	.025	.032	.042
125	.0089	.0098	.011	.013	.015	.019	.023	.029	.037	.046
130	.010	.011	.012	.015	.018	.022	.027	.034	.044	
135	.011	.013	.015	.017	.021	.026	.032	.041		
140	.013	.015	.017	.021	.025	.031	.039			
145	.016	.018	.021	.025	.031	.038				
150	.020	.023	.026	.031	.038	.047				

π_R (Resistance Factor)

Resistance Range (ohms)	π_R
up to 10K	1.0
>10K to 100K	1.7
>100K to 1 meg	3.0
>3 meg	5.0

π_E (Environmental Factor)

Environment	π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	6.0
Airborne, Inhabited	15.0
Naval, Sheltered	16.0
Ground, Mobile	26.0
Naval, Unsheltered	23.0
Airborne, Uninhab.	30.0
Missile, launch	73.0

π_Q (Quality Factor)

Failure Rate Level	π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-93	5.0

FIGURE 5.2-6 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL
FOR FIXED, WIREWOUND (Power Type) RESISTORS
(MIL-R-39007, Style RWR and MIL-R-26, Style RW)

$$\lambda_p = \lambda_b \, (\pi_R \times \pi_E \times \pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0026	.0032	.0040	.0048	.0059	.0073	.0089	.010	.013	.016
10	.0028	.0035	.0043	.0053	.0066	.0081	.0099	.012	.015	.018
20	.0030	.0038	.0047	.0058	.0073	.0090	.011	.013	.017	.021
30	.0033	.0041	.0051	.0064	.0081	.010	.012	.015	.019	.024
40	.0036	.0045	.0056	.0071	.0090	.011	.014	.017	.022	
50	.0038	.0049	.0062	.0079	.010	.012	.016	.020	.025	
60	.0042	.0053	.0068	.0087	.011	.014	.018	.023		
70	.0045	.0059	.0075	.0097	.012	.016	.020	.026		
80	.0050	.0064	.0083	.010	.014	.018	.023			
90	.0054	.0071	.0093	.012	.015	.020	.026			
100	.0059	.0078	.010	.013	.017	.023	.030			
110	.0065	.0086	.011	.015	.020	.026				
120	.0072	.0096	.012	.017	.022	.030				
130	.0079	.010	.014	.019	.025					
140	.0087	.011	.016	.021	.029					
150	.0097	.013	.018	.024	.033					
160	.010	.014	.030	.027						
170	.011	.016	.022	.031						
180	.013	.018	.025							
190	.014	.020	.029							
200	.016	.023	.033							
210	.018	.026								
220	.021	.030								
230	.023									
240	.026									
250	.030									

π_E (Environmental Factor)

Environment	π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	3.0
Airborne, Inhabited	6.0
Naval, Sheltered	7.0
Ground, Mobile	10.0
Naval, Unsheltered	11.0
Airborne, Uninhab.	12.0
Missile, Launch	30.0

π_Q (Quality Factor)

Failure Rate Level	π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-26	5.0

π_R (Resistance Factor)

Style	Resistance Range (ohms)							
	Up to 500	>500 to 1K	>1K to 5K	>5K to 7.5K	>7.5K to 10K	>10K to 15K	>15K to 20K	>20K
RWR 71	1.0	1.0	1.2	1.2	1.6	1.6	1.6	NA
RWR 74	1.0	1.0	1.0	1.2	1.6	1.6	NA	NA
RWR 78	1.0	1.0	1.0	1.0	1.2	1.2	1.2	1.6
RWR 80	1.0	1.2	1.6	1.6	NA	NA	NA	NA
RWR 81	1.0	1.6	NA	NA	NA	NA	NA	NA
RWR 84	1.0	1.0	1.1	1.2	1.2	1.6	NA	NA
RWR 89	1.0	1.0	1.4	NA	NA	NA	NA	NA

FIGURE 5.2-7 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR FIXED, WIREWOUND (Power Type, Chassis Mounted) RESISTORS (MIL-R-39009, Style RER and MIL-R-18546, Style RE)

$$\lambda_p = \lambda_b \left(\pi_R \times \pi_E \times \pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Ratio of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0042	.0052	.0064	.0079	.0099	.0122	.0151	.0188	.0232	.0288
10	.0046	.0057	.0072	.0090	.0112	.0140	.0175	.0218	.0273	.0340
20	.0051	.0064	.0080	.0101	.0127	.0160	.0202	.0254	.0320	.0402
30	.0056	.0071	.0090	.0114	.0145	.0183	.0233	.0295	.0375	.0476
40	.0061	.0079	.0100	.0128	.0164	.0210	.0269	.0344	.0440	
50	.0068	.0087	.0112	.0145	.0187	.0241	.0310	.0400	.0516	
60	.0074	.0097	.0126	.0163	.0212	.0276	.0353	.0465		
70	.008	.011	.014	.018	.024	.032	.041	.054		
80	.009	.012	.016	.021	.027	.036	.048			
90	.010	.013	.018	.023	.031	.041	.055			
100	.011	.015	.020	.026	.035	.047	.064			
110	.012	.016	.022	.030	.040	.054				
120	.013	.018	.025	.034	.046	.062				
130	.015	.020	.028	.038	.052					
140	.016	.022	.031	.043	.059					
150	.018	.025	.034	.048	.067					
160	.020	.027	.039	.054						
170	.022	.030	.043	.061						
180	.024	.034	.048							
190	.026	.038	.054							
200	.029	.042	.060							
210	.032	.046								
220	.035	.051								
230	.038									
240	.042									
250	.047									

Note 1: For characteristic G of MIL-R-18546 and inductively wound styles of MIL-R-39009.

Note 2: For characteristic N of MIL-R-18546 and non-inductively wound styles of MIL-R-39009.

π_Q (Quality Factor)

Failure Rate Level	π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-18546	5.0

π_R (Resistance Factor-Note 1)

Style	Rated Power (W)	Resistance Range (ohms)						
		Up to 100	>100 to 500	>500 to 1K	>1K to 5K	>5K to 10K	>10K to 20K	>20K
RE 60	5	1.0	1.0	1.2	1.2	1.6	NA	NA
RE 65	10	1.0	1.0	1.0	1.2	1.6	NA	NA
RER 65	10	1.0	1.0	1.0	1.2	1.6	NA	NA
RE 70	20	1.0	1.0	1.0	1.2	1.2	1.6	NA
RER 70	20	1.0	1.0	1.0	1.2	1.2	1.6	NA
RE 75	30	1.0	1.0	1.0	1.0	1.1	1.2	1.6
RER 75	30	1.0	1.0	1.0	1.0	1.1	1.2	1.6
RE 77	75	1.0	1.0	1.0	1.0	1.0	1.2	1.6
RE 80	120	1.0	1.0	1.0	1.0	1.0	1.2	1.6

π_E (Environmental Factor)

Environment	π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	3.0
Airborne, Inhabited	6.0
Naval, Sheltered	7.0
Ground, Mobile	10.0
Naval, Unsheltered	11.0
Airborne, Uninhab.	12.0
Missile, Launch	30.0

π_R (Resistance Factor-Note 2)

Style	Rated Power (W)	Resistance Range (ohms)						
		Up to 100	>100 to 500	>500 to 1K	>1K to 5K	>5K to 10K	>10K to 20K	>20K
RE 60	5	1.0	1.0	1.2	1.6	NA	NA	NA
RER 40	5	1.0	1.0	1.2	1.6	NA	NA	NA
RE 65	10	1.0	1.0	1.2	1.6	NA	NA	NA
RER 45	10	1.0	1.0	1.2	1.6	NA	NA	NA
RE 70	20	1.0	1.0	1.0	1.2	1.6	NA	NA
RER 50	20	1.0	1.0	1.0	1.2	1.6	NA	NA
RE 75	30	1.0	1.0	1.0	1.1	1.2	[illegible]	NA
RER 55	30	1.0	1.0	1.0	1.1	1.2	1.4	NA
RE 77	75	1.0	1.0	1.0	1.0	1.2	1.6	NA
RE 80	120	1.0	1.0	1.0	1.0	1.1	[illegible]	NA

FIGURE 5.2-8 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR THERMISTORS (Bead and Disk Type) (MIL-T-23648, Style RTH)

	λ_p (Predicted Failure Rate)	
Environment	Bead Type Style RTH 24, 26, 28, 30, 32, 34, 36, 38 to 40	Disk Type Style RTH 6, 8 and 10
Ground, Benign	0.021×10^{-6}	0.065×10^{-6}
Space Flight	0.021×10^{-6}	0.065×10^{-6}
Ground, Fixed	0.10×10^{-6}	0.31×10^{-6}
Ground, Mobile	0.52×10^{-6}	1.60×10^{-6}
Naval, Sheltered	0.30×10^{-6}	0.90×10^{-6}
Naval, Unsheltered	0.40×10^{-6}	1.20×10^{-6}
Airborne, Inhabited	0.25×10^{-6}	0.75×10^{-6}
Airborne, Uninhab.	0.34×10^{-6}	1.00×10^{-6}
Missile, Launch	1.20×10^{-6}	3.60×10^{-6}

FIGURE 5.2-9 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL **FOR VARIABLE, WIRE-WOUND, (Lead Screw Actuated) RESISTORS (MIL-R-39015, Style RTR and MIL-R-27208, Style RT)**

$$\lambda_p = \lambda_b \; (\Pi_R \times \Pi_V \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0088	.0098	.010	.011	.013	.014	.016	.017	.019	.021
5	.0091	.010	.011	.012	.013	.015	.016	.018	.020	.022
10	.0093	.010	.011	.012	.014	.015	.017	.019	.021	.023
15	.0096	.010	.011	.013	.014	.016	.018	.020	.022	.024
20	.0099	.011	.012	.013	.015	.017	.018	.021	.023	.026
25	.010	.011	.012	.014	.015	.017	.019	.022	.024	.027
30	.010	.011	.013	.014	.016	.018	.020	.023	.025	.029
35	.011	.012	.013	.015	.017	.019	.021	.024	.027	.030
40	.011	.012	.014	.016	.018	.020	.023	.025	.028	.032
45	.012	.013	.015	.017	.019	.021	.024	.027	.030	.034
50	.012	.014	.016	.018	.020	.022	.025	.029	.032	.036
55	.013	.015	.016	.019	.021	.024	.027	.030	.034	.039
60	.014	.015	.017	.020	.022	.025	.029	.033	.037	.042
65	.014	.016	.019	.021	.024	.027	.031	.035	.040	.045
70	.015	.017	.020	.022	.026	.029	.033	.037	.043	.048
75	.016	.019	.021	.024	.027	.031	.036	.040	.046	.052
80	.017	.020	.023	.026	.030	.034	.038	.044	.050	.057
85	.019	.021	.024	.028	.032	.037	.042	.048	.054	.062
90	.020	.023	.026	.030	.035	.040	.045	.052	.059	
95	.022	.025	.029	.033	.038	.043	.050	.057		
100	.024	.027	.031	.036	.041	.048	.055	.063		
105	.026	.030	.034	.040	.046	.052	.060			
110	.028	.033	.038	.044	.050	.058				
115	.031	.036	.042	.048	.056					
120	.035	.040	.047	.054	.062					
125	.039	.045	.052	.060						
130	.043	.050	.058							
135	.049	.057								
140	.055									
145	.063									

*V Rated = 40V. for RT26 & 27
= 90V. for RTR12, 22 & 24; RT12 & 22

Π_R **-(Resistance Factor)**

Resistance Range (ohms)	Π_R
10 to 2K	1.0
>2K to 5K	1.4
>5K to 20K	2.0

Π_V **(Voltage Factor)**

Ratio of Applied Voltage to Rated Voltage *	Π_V
1.0	2.00
0.9	1.40
0.8	1.22
0.7	1.10
0.6 to 0.3	1.00
0.2	1.05
0.1	1.10
0	1.40

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-R-27208	5.0

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	3.0
Airborne, Inhabited	6.0
Naval, Sheltered	7.0
Ground, Mobile	8.0
Naval, Unsheltered	10.0
Airborne, Uninhab.	12.0
Missile, Launch	60.0

FIGURE 5.2-10 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR PRECISION WIREWOUND POTENTIOMETERS (MIL-R-12934, Style RR)

$$\lambda_p = \lambda_b \; (\Pi_{taps} \times \Pi_R \times \Pi_V \times \Pi_C \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.126	.133	.140	.148	.156	.164	.173	.182	.192	.203
40	.137	.145	.154	.164	.173	.184	.195	.207	.220	.233
50	.150	.160	.171	.183	.195	.209	.223	.238	.254	.272
60	.166	.179	.192	.207	.223	.240	.258	.278	.299	.322
70	.186	.202	.219	.237	.258	.279	.303	.329	.357	.387
80	.211	.230	.252	.276	.302	.330	.361	.395	.433	.473
90	.242	.267	.295	.325	.359	.397	.438	.484	.534	.590
100	.281	.313	.349	.389	.434	.484	.540	.603		
110	.331	.373	.420	.474	.534	.602				
120	.396	.451	.515	.587						
130	.481	.556	.641							
140	.596									

Π_{taps}

N_{taps}	Π_{taps}	N_{taps}	Π_{taps}	N_{taps}	Π_{taps}
3	1.00	13	2.67	23	5.20
4	1.11	14	2.88	24	5.49
5	1.24	15	3.12	25	5.79
6	1.38	16	3.35	26	6.09
7	1.53	17	3.59	27	6.40
8	1.69	18	3.85	28	6.72
9	1.87	19	4.10	29	7.04
10	2.06	20	4.37	30	7.36
11	2.25	21	4.64	31	7.69
12	2.45	22	4.92	32	8.03

Π_V (Voltage)

Ratio of Applied Voltage to Rated Voltage *	Π_V
1.0	2.00
0.9	1.40
0.8	1.22
0.7	1.10
0.6 to 0.3	1.00
0.2	1.05
0.1	1.10

* V Rated = 250V. for RR0900, 1100, 1300, 2000 & 3000
= 500V. for RR1000, 1400 & 2100

Π_C (Construction Factor)

Construction Class	Π_C
RR0900A12A7J103	4.0
2	2.0
3	1.0
4	6.0
5	3.0
6	1.5

Π_R (Resistance Factor)

Resistance Range (ohms)	Π_R
100 to 10K	1.0
>10K to 20K	1.1
>20K to 50K	1.4
>50K to 100K	2.0
>100K to 200K	2.5
>200K to 500K	3.5

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1.0
Space Flight	1.0
Ground, Fixed	5.0
Airborne, Inhabited	10.0
Naval, Sheltered	10.0
Ground, Mobile	10.0
Naval, Unsheltered	12.0
Airborne, Uninhab.	15.0
Missile, Launch	120.0

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec.	2.5
Lower	5.0

FIGURE 5.2-11 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR SEMIPRECISION WIREWOUND POTENTIOMETERS (MIL-R-19, Style RA and MIL-R-39002, Style RK)

$$\lambda_p = \lambda_b\ (\Pi_{taps} \times \Pi_R \times \Pi_V \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (^oC)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.062	.069	.077	.086	.096	.107	.120	.134	.149	.167
35	.065	.073	.082	.092	.104	.117	.132	.149	.167	.189
40	.068	.077	.088	.100	.113	.129	.146	.166	.189	.215
45	.072	.082	.095	.108	.124	.143	.164	.188	.215	.247
50	.076	.088	.102	.118	.137	.159	.184	.213	.247	.286
55	.081	.095	.111	.130	.152	.178	.208	.244	.285	.334
60	.086	.102	.121	.143	.170	.201	.238	.281	.333	.394
65	.093	.111	.133	.159	.191	.228	.273	.327	.391	.469
70	.100	.121	.147	.178	.215	.261	.317	.384	.465	.563
75	.108	.133	.163	.200	.245	.301	.370	.454	.557	.684
80	.118	.146	.182	.226	.282	.351	.436	.543	.675	.840
85	.129	.162	.205	.258	.326	.411	.519	.655	.826	1.043
90	.141	.181	.232	.297	.380	.487	.623	.798	1.023	
95	.156	.203	.264	.344	.447	.581	.756	.984		
100	.173	.229	.303	.401	.530	.701	.927			
105	.194	.261	.351	.472	.635	.854				
110	.218	.299	.409	.560	.767					
115	.247	.345	.481	.671						
120	.282	.401	.571							
125	.324	.470								
130	.375									

Π_{taps}

N_{taps}	Π_{taps}	N_{taps}	Π_{taps}	N_{taps}	Π_{taps}
3	1.00	13	2.67	23	5.20
4	1.11	14	2.88	24	5.49
5	1.24	15	3.12	25	5.79
6	1.38	16	3.35	26	6.09
7	1.53	17	3.59	27	6.40
8	1.69	18	3.85	28	6.72
9	1.87	19	4.10	29	7.04
10	2.06	20	4.37	30	7.36
11	2.25	21	4.64	31	7.69
12	2.45	22	4.92	32	8.03

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec.	2.0
Lower	4.0

Π_R (Resistance Factor)

Resistance Range (ohms)	Π_R
10 to 2K	1.0
>2K to 5K	1.4
>5K to 10K	2.0

Π_V (Voltage Factor)

Ratio of Applied Voltage to Rated Voltage *	Π_V
1.0	2.00
0.9	1.40
0.8	1.22
0.7	1.10
0.6 to 0.3	1.00
0.2	1.05
0.1	1.10

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1.0
Space Flight	N/A
Ground, Fixed	6.0
Airborne, Inhabited	15.0
Naval, Sheltered	18.0
Ground, Mobile	20.0
Naval, Unsheltered	N/A
Airborne, Uninhab.	N/A
Missile, Launch	N/A

* V Rated = 50 for RA10
= 75 for RA20X-XC,F
= 130 for RA30X-XC,F

V Rated = 175 for RA20X-XA
= 275 for RK09
= 320 for RAX-XA

FIGURE 5.2-12 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR POWER WIREWOUND POTENTIOMETERS (MIL-R-22, Style RP)

$$\lambda_p = \lambda_b (\Pi_{taps} \times \Pi_R \times \Pi_V \times \Pi_C \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.076	.083	.091	.099	.109	.119	.131	.143	.157	.172
40	.081	.089	.099	.109	.121	.134	.148	.163	.180	
50	.087	.097	.109	.121	.135	.151	.168	.188	.210	
60	.095	.107	.121	.136	.153	.172	.194	.219	.247	
70	.104	.119	.135	.154	.175	.199	.227	.259		
80	.116	.133	.153	.176	.203	.234	.269	.310		
90	.130	.151	.176	.205	.238	.277	.323	.376		
100	.147	.173	.204	.241	.284	.334	.394			
110	.169	.201	.240	.287	.343	.409	.488			
120	.196	.237	.287	.347	.420	.509	.615			
130	.231	.284	.348	.427	.524	.643				

Π_{taps}

N_{taps}	Π_{taps}	N_{taps}	Π_{taps}	N_{taps}	Π_{taps}
3	1.00	13	2.67	23	5.20
4	1.11	14	2.88	24	5.49
5	1.24	15	3.12	25	5.79
6	1.38	16	3.35	26	6.09
7	1.53	17	3.59	27	6.40
8	1.69	18	3.85	28	6.72
9	1.87	19	4.10	29	7.04
10	2.06	20	4.37	30	7.36
11	2.25	21	4.64	31	7.69
12	2.45	22	4.92	32	8.03

Π_V **(Voltage Factor)**

Ratio of Applied Voltage to Rated Voltage *	Π_V
1.0	2.00
0.9	1.40
0.8	1.22
0.7	1.10
0.6 to 0.3	1.00
0.2	1.05
0.1	1.10

*V Rated = 250V for RP06 & 10
= 500V for others

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1.0
Space Flight	N/A
Ground, Fixed	6.0
Airborne, Inhabited	15.0
Naval, Sheltered	18.0
Ground, Mobile	20.0
Naval, Unsheltered	N/A
Airborne, Uninhab.	N/A
Missile, Launch	N/A

Π_C **(Construction Factor)**

Construction Class	Style	Π_C
Enclosed	**RP07, RP11, RP16**	2.0
Unenclosed	All other Styles	1.0

Π_R **(Resistance Factor)**

Resistance Range (ohms)	Π_R
1 to 2K	1.0
>2K to 5K	1.4
>5K to 10K	2.0

Π_Q **(Quality Factor)**

Quality Level	Π_Q
Upper	1.0
Mil-Spec.	2.0
Lower	4.0

FIGURE 5.2-13 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR VARIABLE (NON WIREWOUND TRIMMERS) RESISTORS (MIL-R-22097, Style RJ)

$$\lambda_p = \lambda_b \, (\Pi_{taps} \times \Pi_R \times \Pi_V \times \Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (^oC)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.506	.521	.557	.585	.614	.644	.675	.709	.744	.780
40	.527	.555	.584	.615	.648	.683	.719	.758	.798	.841
50	.552	.584	.618	.653	.691	.731	.773	.818	.866	.916
60	.584	.621	.660	.701	.744	.791	.840	.893	.949	1.01
70	.625	.667	.712	.760	.811	.866	.924	.987	1.05	1.12
80	.678	.727	.780	.836	.897	.962	1.03	1.11	1.19	1.27
90	.746	.804	.867	.934	1.01	1.09	1.17	1.26	1.36	
100	.835	.905	.981	1.06	1.15	1.25	1.35	1.46		
110	.954	1.04	1.13	1.23	1.34	1.46				
120	1.12	1.22	1.34	1.47						
130	1.34	1.48	1.63							
140	1.66									

Π_{taps}

N_{taps}	Π_{taps}	N_{taps}	Π_{taps}	N_{taps}	Π_{taps}
3	1.00	13	2.67	23	5.20
4	1.11	14	2.88	24	5.49
5	1.24	15	3.12	25	5.79
6	1.38	16	3.35	26	6.09
7	1.53	17	3.59	27	6.40
8	1.69	18	3.85	28	6.72
9	1.87	19	4.10	29	7.04
10	2.06	20	4.37	30	7.36
11	2.25	21	4.64	31	7.69
12	2.45	22	4.92	32	8.03

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1.0
Space Flight	N/A
Ground, Fixed	3.0
Airborne, Inhabited	6.0
Naval, Sheltered	8.0
Ground, Mobile	10.0
Naval, Unsheltered	12.5
Airborne, Uninhab.	**15.0**
Missile, Launch	**80.0**

Π_R (Resistance Factor)

Resistance Range (ohms)	Π_R
10 to 50K	1.0
>50K to 100K	1.1
>100K to 200K	1.2
>200K to 500K	1.4
>500K to 1 meg	1.8

Π_V (Voltage Factor

Ratio of Applied Voltage to Rated Voltage *	Π_V
1.0	1.20
0.9	1.05
0.8 to 0.1	1.00

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec.	**2.0**
Lower	**4.0**

***V Rated** = 200V for RJ26 & 50
* 300V for RJ12,22,& 24

FIGURE 5.2.14 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR COMPOSITION (LOW PRECISION) POTENTIOMETERS (MIL-R-94, Style RV)

$$\lambda_p = \lambda_b \left(\Pi_{taps} \times \Pi_R \times \Pi_V \times \Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
25	.075	.080	.086	.092	.098	.105	.113	.121	.129	.138
30	.077	.083	.089	.096	.104	.112	.120	.130	.140	.151
35	.079	.086	.093	.101	.110	.119	.129	.140	.152	.165
40	.082	.090	.098	.107	.117	.128	.140	.153	.167	.182
45	.085	.094	.103	.114	.125	.138	.152	.168	.185	.203
50	.089	.099	.110	.122	.135	.150	.167	.186	.206	.229
55	.09[illegible]	.105	.117	.132	.147	.165	.185	.208	.233	.261
60	.099	.112	.126	.143	.162	.183	.207	.234	.265	.300
65	.105	.120	.137	.157	.179	.205	.234	.268	.306	.350
70	.113	.130	.150	.174	.201	.232	.268	.310	.358	.413
75	.122	.142	.166	.194	.227	.265	.310	.363	.424	
80	.133	.157	.186	.220	.260	.308	.364	.431		
85	.146	.175	.210	.252	.302	.362	.434			
90	.163	.198	.241	.292	.355	.432				
95	.184	.226	.279	.344	.425					
100	.21[illegible]	.263	.329	.412						
105	.243	.310	.395							
110	.287	.372								
115	.344									

Π_{taps}

N_{taps}	Π_{taps}	N_{taps}	Π_{taps}	N_{taps}	Π_{taps}
3	1.00	13	2.67	23	5.20
4	1.11	14	2.88	24	5.49
5	1.24	15	3.12	25	5.79
6	1.38	16	3.35	26	6.09
7	1.53	17	3.59	27	6.40
8	1.69	18	3.85	28	6.72
9	1.87	19	4.10	29	7.04
10	2.06	20	4.37	30	7.36
11	2.25	21	4.64	31	7.69
12	2.45	22	4.92	32	8.03

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1.0
Space Flight	N/A
Ground, Fixed	10.0
Airborne, Inhabited	50.0
Naval, Sheltered	50.0
Ground, Mobile	50.0
Naval, Unsheltered	55.0
Airborne, Uninhab.	60.0
Missile, Launch	100.0

Π_V* (Voltage Factor)

Ratio of Applied Voltage to Rated Voltage	Π_V
1.0	1.20
0.9	1.05
0.8 to 0.1	1.00

Π_R (Resistance Factor)

Resistance Range (ohms)	Π_R
50 to 50K	1.0
>50K to 100K	1.1
>100K to 200K	1.2
>200K to 500K	1.4
>500K to 1 meg	1.8

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec.	2.5
Lower	3.0

* V Rated = 500 for RV4x--xA
= 350 for RV2,RV5,RV6x--xA;RV4x--C & F
= 250 for RV1x--xA
= 200 for all other types

5.2.3 Calculation of Stress Ratio for Potentiometers

The stress ratio (S) is defined by the equation:

$$S = \frac{P_{applied}}{\Pi_{eff} \cdot \Pi_{ganged} \cdot P_{rated}}$$

where:

$P_{applied}$	is the equivalent power input to the potentiometer when it is not loaded (i.e., wiper lead disconnected). Its value is computed as the square of the input voltage, divided by the potentiometer total resistance.
	$W_{operate} = (V_{in}^2/R_P)$.
P_{rated}	is the power rating of the potentiometer.
Π_{ganged}	is a correction factor to correct for the reduction in effective rating of the potentiometer due to the close proximity of two or more potentiometers when they are ganged together on a common shaft. the values of Π_{ganged} are obtained from Table 5.2-6.
Π_{eff}	is a correction factor for the electrical loading effect on the wiper contact of the potentiometer. Its value is a function of the type of potentiometer, its resistance, and the load resistance. The value of Π_{eff} may be computed as follows:

$$\Pi_{eff} = \frac{R_L^2}{R_L^2 + K_H (R_p^2 + 2R_pR_L)}$$

where:

K_H is a constant dependent upon the style shown in Table 5.2-4.

R_L = load resistance (If R_L is variable, use lowest value).

R_P = potentiometer resistance

The value of Π_{eff} can be obtained directly from Table 5.2-5.

TABLE 5.2-4

Potentiometer Type (Mil Spec)	Style	K_H
MIL-R-19	RA	0.5
MIL-R-22	RP	1.0
MIL-R-94	RV	0.5
MIL-R-12934	RR1000,2100, 1001, 2101, 2102, 2103, 1400, 1003	0.3
MIL-R-12934	All other types	0.2
MIL-R-22097	RJ11, RJ12	0.3
MIL-R-22097	All other types	0.2
MIL-R-27208	RT22, 24, 26, 27	0.2
MIL-R-27208	All other types	0.3
MIL-R-39002	RK	0.5
MIL-R-39015	RTR22, 24	0.17
MIL-R-39015	RTR12	0.3

TABLE 5.2-5. LOADED POTENTIOMETER DERATING FACTOR, Π_{eff}.

R_L/R_P	K_H				
	0.5	01.0	0.167	0.2	0.3
0.1	.02	.008	.05	.04	.03
0.2	.05	.03	.15	.13	.07
0.3	.10	.05	.25	.22	.16
0.4	.15	.08	.35	.31	.23
0.5	.20	.11	.43	.38	.29
0.6	.25	.14	.49	.45	.35
0.7	.29	.17	.55	.51	.40
0.8	.33	.20	.60	.55	.45
0.9	.37	.22	.63	.59	.49
1.0	.40	.25	.67	.63	.53
1.5	.53	.36	.77	.74	.65
2.0	.62	.44	.83	.80	.72
3.0	.72	.56	.89	.87	.81
4.0	.78	.64	.91	.90	.86
5.0	.82	.69	.93	.92	.88
10.0	.90	.83	.96	.96	.94
100.0	.99	.98	1.00	1.00	.99

TABLE 5.2-6. GANGED-POTENTIOMETER FACTOR, Π_{ganged}

Number of Sections	First Potentiometer Next to Mount	Second in Gang	Third in Gang	Fourth in Gang	Fifth in Gang	Sixth in Gang
Single	1.0	Not Applicable				
Two	0.75	0.60	Not Applicable			
Three	0.75	0.50	0.60	Not Applicable		
Four	0.75	0.50	0.50	0.60	Not Applicable	
Five	0.75	0.50	0.40	0.50	0.60	Not Applicable
Six	0.75	0.50	0.40	0.40	0.50	0.60

5.3 Operational/Non-Operational Failure Rate Comparison

Table 5.3-1 presents the operational failure rates with the operation to non-operation failure rate ratio. The operational failure rates were calculated using the MIL-HDBK-217B prediction models and the following assumptions:

For carbon composition, film and wirewound resistors, a quality level 'M' with less than 100K resistance at 25°C was assumed with a 50 percent ratio of operating to rated wattage.

For variable resistors, a precision wirewound potentiometer with 3 taps, upper quality, less than 10K resistance and 50 percent derating was assumed.

The launch operation factors were extracted directly from MIL-HDBK-217B.

TABLE 5.3-1. RESISTOR OPERATING AND NON-OPERATING FACTORS

DEVICE CATEGORY RESISTORS	NON-OPERATING FAILURE RATE x 10^{-9}	GROUND, FIXED, OPERATING FAILURE RATE x 10^{-9}	G.F.-OPERATING TO NON-OPERATING RATIO	MISSILE LAUNCH TO G.F. OPERATING RATIO
Composition				
RC	0.22	10.0	45.5	9.
RCR	<0.066	0.20	3.0	9.
Film				
RL	0.11	75.0	681.8	7.3
RN	0.11	17.0	154.5	7.0
RLR	0.017	1.5	88.2	7.3
RNR	0.017	1.7	100.0	7.0
Wirewound				
RB	1.19	280.	235.3	12.1
RW	1.19	170.	142.9	10.0
RE	1.19	310.	260.5	10.6
RBR	0.20	5.6	28.0	12.1
RWR	0.20	3.3	16.5	10.0
RER	0.20	6.2	31.0	10.6
Thermistor				
MIL-STD	133.3	310.	2.3	11.6
RTH	<16.9	100.	5.9	12.0
Variable				
RJ	3.79	2300.	606.9	21.7
RT	3.79	330.	87.1	27.3
RTR	3.71	6.6	1.8	21.2
Potentiometer				
RR	<8.40	1100.	131.0	25.5
RA & RK	<8.40	1600.	190.5	N/A
RP	<8.40	1100.	131.0	N/A
RV	<8.40	8000.	95.2	2.0

6.0 Capacitors

Capacitors used in electronic equipment are usually categorized into types based on the dielectric material used and their physical construction.

The following summarizes some characteristics of specific capacitor types.

Film dielectric capacitors with paper, paper/plastic, or plastic dielectrics are commonly made by interleaving thin films of dielectric material with metallic foils which serve as electrodes. The resulting four-layer wedge is spiral-wound into a tight cylindrical roll. Leads are attached to this capacitor section by soldering or welding. There are two basic internal constructions. The inserted tab construction utilizes flat metal tabs which are laid against the electrode during winding. These tabs are brought out within one turn of each other and are connected to external leads. The tabs are usually connected to the electrodes without solder. In the extended foil type of construction, the electrode foils are offset from each other such that the end of each electrode turn is exposed only at one end of the roll assembly. The leads are attached at opposite ends and connect all turns of each electrode in parallel.

Paper dielectric capacitors have several constructions: metallic cases with leads existing through glass-to-metal hermetic seals, mylar wrap encasement, and polystyrene.

Electrolytic capacitors include aluminum, non-solid tantalum and solid tantalum.

Glass and mica dielectric capacitors have non-flexible dielectric materials. To obtain the higher capacitance units, thin layers of the dielectric are stacked between multiple electrodes. Alternate electrodes are connected in parallel. The electrodes can be either metallic foil or a metallic film painted directly on the dielectric. The assembled stack of electrodes and dielectrics is held in close contact by clamps or by the capacitor encasement.

Mica dielectric capacitors are available either with a molded encasement or with a conformal dipped encasement.

Glass and procelain dielectric capacitors are encased in glass and the leads are pretreated to give a good glass-to-metal seal. This provides high resistance to humidity. Flexible or semi-rigid conformal coating is recommended for these capacitors.

Ceramic dielectric capacitors are generally available either as tubular designs, as flat disc designs, or as flat plate designs. Mechanically the tubular designs consist of a ceramic tube with silver bands (electrodes) fired on the inside and outside surfaces. Capacitance is formed between the silver bands with the ceramic as the dielectric. Leads are wrapped around each end and soldered to the bands. Leads exit radically from the tube and are parallel. The assembly is encapsulated in Durez resin which is subsequently vacuum-impregnated with a high melting point wax. The disc capacitors consist of a disc with a thin coating of metallic paint fired on each face. Parallel leads are soldered to the metallic electrodes. The assembly is encapsulated in Durez and impregnated with a high melting point wax. Flat plate capacitors consist of a monolithic stack in a molded case. The internal stack consists of multiple films of a noble metal spaced with thin films of ceramic. This assembly is fired to give a monolithic construction. Feedthrough or standoff capacitor designs are essentially a modification of one of the above three capacitor types in which one plate of the capacitor becomes an integral part of the chassis.

Variable ceramic dielectric capacitors consist of a thin ceramic disc mounted in contact with a ceramic frame so that it can be rotated about its center. The electrodes consist of semicircular silver patterns. Capacity is changed by varying the overlap of the electrodes. Contact to the rotatable electrode is made by a spring-loaded spider washer which holds disc in contact with adjacent electrode.

Air dielectric variable capacitors consist of a fixed stator with parallel metal plates and a rotor with similar parallel plates located so that these plates are spaced between the stator plates.

Glass piston trimmers consist of a metal piston which moves axially within a glass sleeve. One electrode consists of a metal band either outside or embedded within the glass sleeve. The close fitting piston forms the adjustable electrode of the capacitor.

6.1 Storage Reliability Analysis

6.1.1 Failure Mechanisms

Capacitors are susceptible to water vapor. Even in hermetically-sealed units, moisture present during manufacture can lead to deterioration of insulation or dielectric materials. This can be a more serious consideration in certain poorer grade capacitors.

The entrance of moisture through cracks in the seals can be minimized in several ways. Capacitors with seal cracks prior to installation in equipment should be screened out and removed from manufacturing stock. Cracks developed during assembly into equipment can be prevented by careful process control and sometimes can be screened out by final assembly inspection. Cracks which develop during use in later life of the equipment can sometimes be traced to low-quality seals or stresses placed on the leads during equipment manufacture. Certain seal cracks are traceable to a combination of these causes plus stress resulting from use environment.

Electrolytic capacitors have experienced problems in storage. Table 6.1-1 summarizes the predominant failure mechanism associated with the solid tantalum capacitors. Table 6.1-2 summarizes those for wet tantalum capacitors. Electrolyte leakage in the wet tantalum capacitor has been the major source of problems while impurities in the solid tantalum capacitor has caused problems. Most of the failure mechanisms associated with these capacitors are accelerated to failure by a temperature cycling environment. Continuing R&D on these devices in recent years has brought about a significant increase in reliability.

6.1.2 Non-Operating Failure Rate Predictions

The non-operating failure rate table for various types of capacitors is shown in Table 6.1-3.

TABLE 6.1-1.

FAILURE MECHANISM ANALYSIS, SOLID TANTALUM CAPACITORS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
Oxide Defects	Impurities in starting tantalum impede oxide growth at sites during anodization.	Temperature cycling, burn in, surge test	Out-of-tolerance	High leakage currents, or outliers
	Abrasions of sintered pellets expose impurities prior to anodization.			
	Binder or die impurities on sintered pellet.			
	Handling damage during anodization processes and assembly.			
	Crystalline tantalum pentoxide.			
	Oxide shorts due to excessive power surges under flicker or scintillation conditions.	Surge test	Short	Short circuits
	Thin MnO_2 or silver paint penetrating MnO_2 and preventing healing of defect sites.	Temperature cycling, burn in, surge test	Out-of-tolerance	High leakage currents, or outliers. High dissipation factor.
Poor Slug Adhesion	Inadequate wetting of solder to silver paint.	Temperature cycling, burn in	Out-of-tolerance	Dissipating, capacitance, radiographic inspection
	Silver paint dissolving into the solder.			
	Low solder level, poor anchorage of slug to case, flux between solder and paint	Temperature cycling, burn in		Radiographic inspection

TABLE 6.1-1.

FAILURE MECHANISM ANALYSIS, SOLID TANTALUM CAPACITORS (cont'd.)

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
Solder Reflow	Excessive heat applied during assembly of capacitor into circuit.			Radiographic inspection
Mechanical Defects	Solder distributions, voids, slugs canted in case, bent risers, etc.			Radiographic inspection

TABLE 6.1-2.

FAILURE MECHANISM ANALYSIS, TANTALUM FOIL CAPACITORS

FAILURE MECHANISM	CAUSE	ACCELERATING ENVIRONMENT	FAILURE MODE	DETECTION METHOD
Electrolyte Leakage	Leakage past center of seal causing electrolyte to bridge between internal nickel wire and case.	Temperature cycling, burn in	Shorts, open, capacitance, leakage	Visual inspection, electrical test
Insulation Defects	Metallic contamination in mylar sleeving, improperly cured cured epoxy compound	Temperature cycling, burn in	Short, dissipation factor	Electrical test
Foil Separation	Reactive impurities in electrolyte or in paper spacer	Temperature cycling, burn in	Capacitance, dissipation factor	Electrical test
Faulty Lead to Foil Welds	Machine and operator errors cause inadequate welds	Temperature cycling, burn in	Open	Visual, electrical test

TABLE 6.1-3. CAPACITOR NON-OPERATING FAILURE RATES

TYPE & STYLE	λ IN FITS	90% ONE-SIDED CONFIDENCE λ IN FITS
Paper & Plastic		
CQ	4.10	6.67
CPV & CQR	1.11	2.96
Mica		
CM & CB	(<0.38)	0.89
CMR	(<0.38)	0.89
Glass		
MIL-STD	(<0.81)	1.88
CYR	(<0.81)*	1.88
Ceramic		
CC & CK	2.14	4.76
CKR	0.32	0.86
Solid Tantalum		
MIL-STD	(<2.80)	6.46
CSR	0.13	0.51
Non-Solid Tantalum		
CL	12.5	25.0
CLR	8.98	18.0
Aluminum Oxide		
CU	(<6.46)	14.9
Aluminum Dry Elect.		
CE	TBD	-
Titanium	(<19.6)	45.3
Tubular Temp.	(<78.1)	180.4
Differential, Dual Mode	(<15.7)	36.2
Metallized Polycarbonite	18.5	49.1
Network Capacitor	(<909.1)	-
Variable, Ceramic		
CV	(<3333.)	-
Variable, Piston		
PC	(<5.65)	13.0
Variable, Air	35.8	95.3

6.1.3 Non-Operating Failure Rate Data

The failure rate table in Section 6.1.2 is based on storage data consisting of approximately 33 billion part hours with 32 failures reported. Storage hours and failure data for each type of capacitor is shown in Table 6.1-4.

Data was obtained from eight sources and are listed in Tables 6.1-5 through 6.1-12. Details of environments for each source are given below:

Missile D data consists of 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes approximately 1.31 billion capacitor storage hours with two failures reported. The mica capacitor failure was recorded as "changed value." The variable capacitor failure was listed as "shorted."

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included nearly 4.3 billion part hours with six failures reported. All of the devices in missile E-1 are rated MIL-STD.

Missile F data consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southeast desert under open sided metal roof sheds; 30 missiles stored outside in the canal zone under open sided metal roof sheds; and 30 missiles stored in the southeast U. S. in bunkers. The data includes over 300 million capacitor storage hours with one failure reported. The failure was recorded in the missiles stored in the Arctic with no failure mode given.

TABLE 6.1-4. CAPACITOR NON-OPERATING DATA SUMMARY

TYPE & STYLE OR QUALITY	TOTAL HOURS x 10^6	NUMBER OF FAILURES	STYLE	TOTAL HRS.x 10^6	NUMBER OF FAILURES	λ IN FITS
Paper & Plastic						
MIL-STD	1949.7	8				
CPV	61.8	0				
CQR	1271.9	0	CQ	1949.7	8	4.10
CHR	165.3	0	CPV & CQR	1797.0	2	1.11
HI-REL	278.0	2				
Mica						
CM	2309.5	0				
MIL-STD	297.0	0	CM & CB	2606.5	0	(<0.38)
HI-REL	664.6	2	CMR	664.6	2	3.01
Glass						
MIL-STD	1230.0	0	MIL-STD	1230.0	0	(<0.81)
HI-REL	367.2	0	CYR	367.2	0	(<2.72)
Ceramic						
MIL-STD	1397.8	3	CC & CK	1400.0	3	2.14
CK	2.2	0	CKR	6163.1	2	0.32
HI-REL	4030.0	2	CC & CKR	7299.3	2	0.27
CKR	2133.1	0				
CC & CKR	7299.3	2				
Solid Tantalum						
MIL-STD	357.3	0	MIL-STD	357.3	0	(<2.80)
HI-REL	2132.7	1	CSR	7686.7	1	0.13
CSR	5554.0	0				

TABLE 6.1-4. CAPACITOR NON-OPERATING DATA SUMMARY (cont'd)

TYPE & STYLE OR QUALITY	TOTAL HOURS x 10^6	NUMBER OF FAILURES	STYLE	TOTAL HRS. x 10^6	NUMBER OF FAILURES	λ IN FITS
Non-Solid Tantalum						
MIL-STD	307.1	2	CL	319.4	4	12.5
CL	12.3	2	CLR	445.5	4	8.93
HI-REL	445.5	4				
Variable Ceramic			CV	.3	0	(<3333.)
Variable Piston			PC	177.1	0	(<5.65)
Variable, Air				55.8	2	35.8
Aluminum Oxide			CU	154.8	0	(<6.46)
Aluminum Dry Electro.			CE	-	-	-
Titanium				51.0	0	(<19.6)
Tubular Temp.				12.8	0	(<78.1)
Differential, Dual Mode				63.8	0	(<15.7)
Metallized Polycarbonite				108.4	2	18.5
Network Capacitor				1.1	0	(<909.1)

TABLE 6.1-5. MISSILE D CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Mica	18921	230.4	1	434.
Glass	5883	71.6	0	(<6.80)
Ceramic	74730	909.9	0	(<1.1)
Tantalum, Solid	7314	89.1	0	(<11.2)
Tantalum, Non-Solid	1272	15.5	0	(<64.6)
Variable, Air	795	9.7	1	103.3

TABLE 6.1-6. MISSILE E-1 CAPACITOR NON-OPERATING DATA (MIL-STD)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Paper	110998	1620.6	6	3.70
Glass	83904	1225.	0	(<.82)
Ceramic	44574	650.8	0	(<1.54)
Titanium	3496	51.0	0	(<19.6)
Tubular Temp.	874	12.8	0	(<78.4)
Tantalum, Solid	24472	357.3	0	(<2.80)
Tantalum, Non-Solid	20976	306.3	0	(<3.27)
Differential, Dual Mode	4370	63.8	0	(<15.6)

TABLE 6.1-7. MISSILE F CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Plastic	2880	63.1	1	15.9
Mica	3000	65.7	0	(<15.2)
Ceramic (CKR)	6000	131.4	0	(<7.6)
Solid Tantalum (CSR)	2880	63.1	0	(<15.9)

TABLE 6.1-8. MISSILE G CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Plastic	1131	32.4	0	(<30.8)
Mica (?)	78	2.2	0	(<447.2)
Mica (CM)	78	2.2	0	(<447.2)
Ceramic (CKR)	156	4.5	0	(<223.6)
Ceramic (CK)	78	2.2	0	(<447.2)
Ceramic (?)	156	4.5	0	(<223.6)
Tantalum, Solid (CSR)	195	5.6	0	(<178.8)
Tantalum, Non-Solid (CL)	429	12.3	2	162.5
Network Capacitor	39	1.1	0	(<894.5)

TABLE 6.1-9. MISSILE H CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Paper (CQR)	38556	1271.9	0	(<0.78)
Mica (CM)	80325	1071.9	0	(<0.93)
Ceramic (CKR)	418761	6652.7	2	.27
Ceramic (CC)	41769	646.6		
Tantalum, Solid (CSR)	245259	3896.4	0	(<0.26)
Variable, Glass	5355	85.1	0	(<11.75)

TABLE 6.1-10. MISSILE I CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Ceramic (CKR)	200790	1997.2	0	(<0.50)
Solid Tantalum (CSR)	486450	4838.7	0	(<0.21)
Mica (CM)	124200	1235.4	0	(<0.81)
Paper (CHR)	18630	185.3	0	(<5.40)
Paper (CP)	6210	61.8	0	(<16.19)
Plastic	12420	123.5	0	(<8.09)
Metallized Polycarbonite	8280	82.4	1	12.14

TABLE 6.1-11. SOURCE A CAPACITOR NON-OPERATING DATA

	MIL-STD			HI-REL		
DEVICE TYPE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Paper	329.	2	6.08	19.	0	(<52.6)
Plastic	-	-	-	30.	1	33.3
Polycarbon Film	-	-	-	24.	1	41.7
Mylar	.1	0	(<100.)	-	-	-
Polystyrene	-	-	-	10.	0	(<100.)
Metallic Film	-	-	-	2.	0	(<500.)
MICA	297.	0	(<3.37)	354.	1	2.82
MICA, Dipped	-	-	-	9.	0	(<111.)
MICA, Reconstituted	-	-	-	.4	0	(<2.5)
Glass	5.	0	(<200.)	295.	0	(<3.39)
Ceramic	729.	3	4.12	3103.	2	.64
Feedthrough	-	-	-	12.	0	(<83.3)
Chip	18.	0	(<55.5)	-	-	-
Electrolytic						
General Class	-	-	-	2612.	2	.76
Foil	8.	0	(<125.)	145.	0	(<.69)
Solid Tantalum	-	-	-	2030.	1	.49
Non-Solid Tantalum	.8	2	2500.	430.	4	9.3
Variable						
Piston Trimmer	84.	0	(<11.9)	-	-	-
Air	-	-	-	41.	1	24.4
Ceramic	-	-	-	.3	0	(<3333.)
Glass	-	-	-	8.	0	(<125.)

TABLE 6.1-12. SOURCE D CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Paper	35	1.220	0	(<819.)
MICA	96	2.877	0	(<348.)
Glass	20	.605	0	(<1650.)
Ceramic	20	.626	0	(<1600.)
Tantulum, Solid	400	13.599	0	(<73.5)
Aluminum Oxide	63	1.771	0	(<565.)
Variable, Air	5	.133	0	(<7520.)

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. The data includes 67 million capacitor storage hours with two failures reported.

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. The data includes thirteen and a half billion capacitor storage hours with two failures reported.

Missile I data consists of 2.070 missiles stored for periods from 1 months to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. The data includes more than 85 billion capacitor storage hours with one failure reported.

Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual sources. The data for source A is summarized in Table 6.1-11. Both MIL-STD and HI-REL devices were included.

Source D represents a special test program on devices stored in an environmentally controlled warehouse for up to 5 years. Approximately twenty one million capacitor storage hours were evaluated with no failures reported.

6.2 Capacitor Operational Prediction Models

The MIL-HDBK-217B general failure rate model for capacitors is:

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_{CV} \times \Pi_{SR} \times \Pi_Q) \times 10^{-6}$$

where:

λ_p = device failure rate
λ_b = base failure rate
Π_E = Environmental Adjustment Factor
Π_{CV} = Capacitance Value Adjustment Factor
Π_{SR} = Series Resistance Adjustment Factor
Π_Q = Quality Adjustment Factor

The various types of capacitors require different failure rate models that vary to some degree from the basic models. The specific failure rate model and the Π factor values for each type of capacitor are presented in Figures 6.2-1 through 6.2-16. The base failure rate and adjustment factor values in the figures are based on certain assumptions. See sections 6.2.1 and 6.2.2 for a description of these parameters.

Table 6.2-1 provides a list of capacitor generic types with a cross reference to the corresponding figure number of the failure rate model. As indicated in the table, the models are broken out by capacitor style, characteristic and temperature rating. These can be identified from the capacitor type designation. For example, CQR09 $\underline{A}$ 1 $\underline{M}$ C152K1M indicated style CQR09, "A" rated temperature, and characteristic "M."

6.2.1 Base Failure Rate (λ_b)

The equation for the base failure rate, λ_b, is:

$$\lambda_b = A \ [(\frac{S}{N_S})^H + 1] e^{B(\frac{T + 273}{N_T})^G}$$

where:

A is an adjustment factor for each different type of capacitor, to adjust the model to the proper failure rate.

S represents the ratio of operating to rated voltage.

N_S is a stress constant

e is the natural logarithm base, 2.718

T is the operating ambient temperature in degrees Centigrade

N_T is a temperature constant.

B is a shaping parameter

G and H are acceleration constants.

The quantitative values for the base failure rate model factors are given in Table 6.2-2 for the different capacitor types. The last column of this table lists the figure number that presents the resulting base failure rate values.

6.2.2 Adjustment Factors

6.2.2.1 Environmental Factor Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in the Appendix.

6.2.2.2 Capacitance Value Adjustment Factor, Π_{CV}

Π_{CV} adjusts the model for effect of capacitance related to case size.

6.2.2.3 Series Resistance Adjustment Factor, Π_{SR}

Π_{SR} adjusts the model for the effect of series resistance in circuit application of some electrolytic capacitors.

6.2.2.4 Quality Adjustment Factor, Π_Q

Π_Q accounts for effects of different quality levels.

The Established Reliability (ER) capacitor family generally has four qualification failure rate levels when tested per the requirements of the applicable ER specification. These qualification failure rate levels differ by a factor of ten. However, field data indicates that these failure rate levels differ by a factor about three, hence the Π_Q values have been set accordingly.

TABLE 6.2-1
CAPACITORS OPERATIONAL PREDICTION MODEL CROSS REFERENCE

TYPE	MIL-SPEC	STYLE	FIGURE
Paper and Plastic Film 65° Max Rated	MIL-C-14157	CPV07	6.2-1
	MIL-C-19978	CQ08,09,R,B,-Characteristic P	
Paper and Plastic Film 85°C Max Rated	MIL-C-14157	CPV17	6.2-2
	MIL-C-39022	CHR09 (50 Volt Rated) CHR39 & 49	
	MIL-C-19978	CQ08,09,12,13-Characteristic M CQ72,-Characteristic E CDR32 & 33	
Paper and Plastic Film 125°C Max Rated	MIL-C-39022	CHR09 (above 50 Volt Rated) CHR01, 12,19,29 & 59	6.2-3
	MIL-C-19978	CQ08, 09,12,13,20,72, Characteristic K CQ06 & 07-Characteristic Q CQR01,07,09,12,13,39,42	
MICA	MIL-C-5	CM (Molded)	6.2-4
	MIL-C-39001	CMR (Dipped)	
Button MICA	MIL-C-10950	CB	6.2-5
Glass	MIL-C-23269	CYR	6.2-6
Ceramic (General Purpose) 85°C Max Rated	MIL-C-11015	Designated'A' rated temperature	6.2-7
	MIL-C-39014	CKR13,48,64,72	
Ceramic (General Purpose) 125°C Max Rated	MIL-C-11015	Designated 'B' rated temperature	6.2-8
	MIL-C-39014	CKR05-12,14-16,17-19,73,74	
Ceramic (General Purpose) 150°C Max Rated	MIL-C-11015	Designated 'C' rated temperature	6.2-9

TABLE 6.2-1
CAPACITORS OPERATIONAL PREDICTION MODEL CROSS REFERENCE (CON'T)

TYPE	MIL-SPEC	STYLE	FIGURE
Ceramic, Temperature Compensating	MIL-C-20	CC	6.2-10
Tantalum Electrolytic (Solid)	MIL-C-39003	CSP	6.2-11
Tantalum Electrolytic (Non-Solid)	MIL-C-39006 MIL-C-3965	CLR CL	6.2-12
Aluminum Electrolytic (Aluminum Oxide)	MIL-C-39018	CU	6.2-13
Aluminum Dry Electrolytic	MIL-C-62	CE	6.2-14
Variable Ceramic	MIL-C-81	CV	6.2-15
Variable, Piston Type (Tubular Trimmer)	MIL-C-14409	PC	6.2-16

FIGURE 6.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR PAPER & PLASTIC FILM CAPACITORS -65°C MAX. RATED (MIL-C-14157, Style CPV07 and MIL-C-19978, Style CQ08,09, 12, 13 - Characteristic P)

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)***

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.00006	.00006	.00007	.0001	.0002	.0004	.0010	.0019	.0034	.0057
5	.00006	.00006	.00007	.0001	.0002	.0005	.0010	.0019	.0034	.0058
10	.00006	.00006	.00008	.0001	.0002	.0005	.0010	.0020	.0035	.0060
15	.00006	.00007	.00008	.0001	.0002	.0005	.0011	.0020	.0037	.0062
20	.00007	.00007	.00008	.0001	.0002	.0005	.0011	.0021	.0039	.0065
25	.00007	.00007	.00009	.0001	.0002	.0006	.0012	.0023	.0041	.0070
30	.00008	.00008	.0001	.0001	.0003	.0006	.0013	.0025	.0045	.0076
35	.00009	.00009	.0001	.0001	.0003	.0007	.0015	.0029	.0051	.0086
40	.0001	.0001	.0001	.0002	.0004	.0008	.0017	.0033	.0060	.010
45	.0001	.0001	.0001	.0002	.0005	.0010	.0022	.0041	.0074	.012
50	.0001	.0001	.0002	.0003	.0006	.0014	.0028	.0054	.0097	.016
55	.0002	.0002	.0002	.0004	.0009	.0020	.0041	.0077	.013	.023
60	.0003	.0003	.0004	.0007	.0015	.0031	.0064	.012	.021	.036
65	.0006	.0006	.0008	.0013	.0027	.0057	.011	.022	.039	.066

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	9
Airborne, Uninhab.	15
Missile, Launch	20

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-19978 Non-ER	10.0

* Observe ac voltage limits of Figure 6.2-1-a and corresponding temperature rise from Figure 6.2-1-b in determining stresses for table look-up.

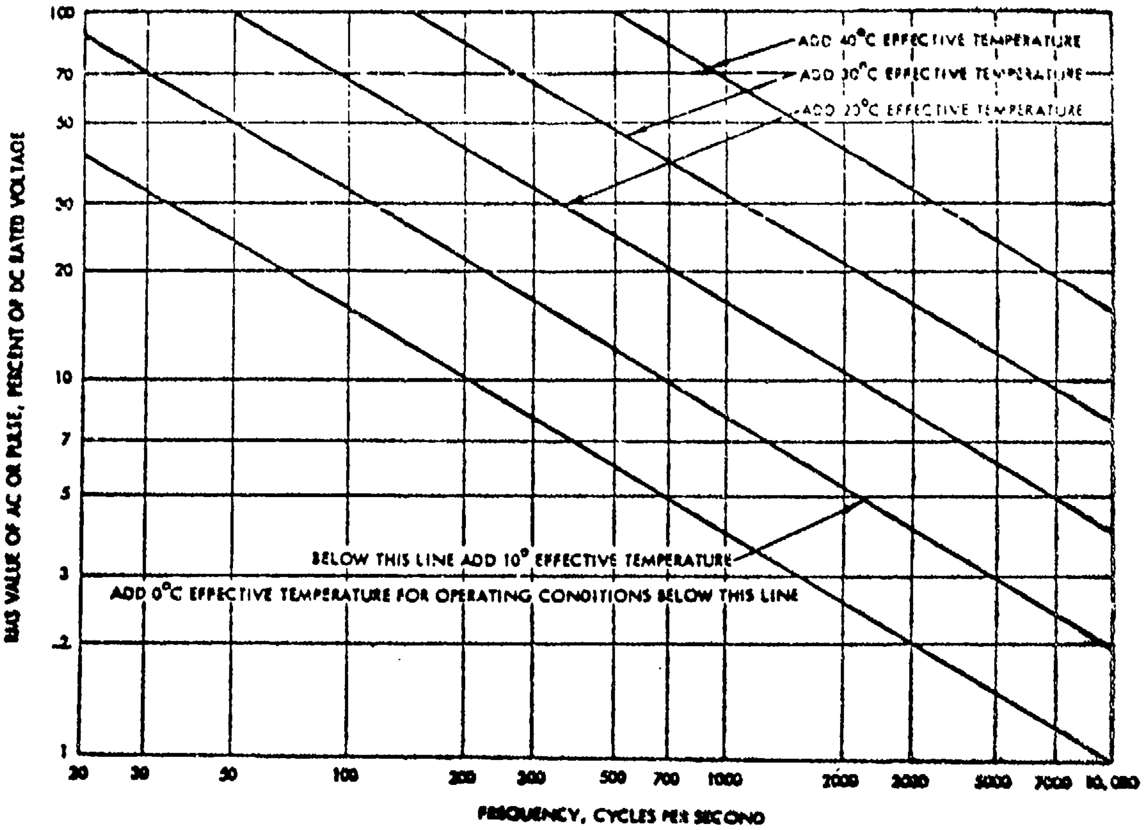


FIGURE 6.2-1a. EQUIVALENT TEMPERATURE INCREASE FOR EFFECTS OF AC OR PULSES FOR PAPER & PLASTIC FILM CAPACITORS (Applicable to MIL-C-14157 & MIL-C-19978, Chars. E, K, M & Q; MIL-C-39022 All styles).

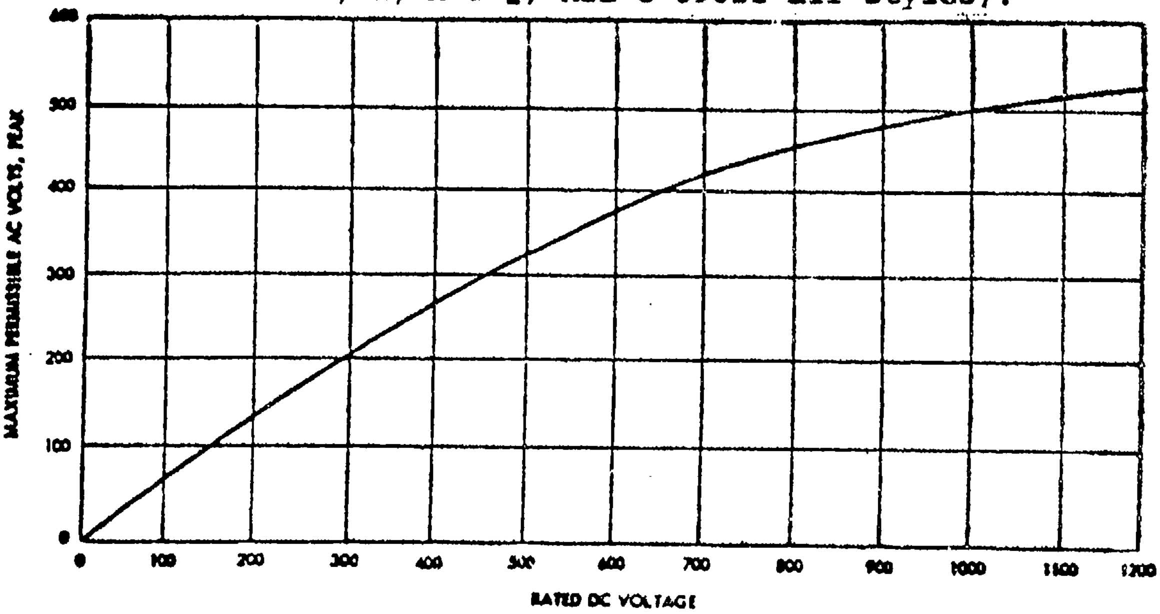


FIGURE 6.2-1b. BASIC RESTRICTION ON USE OF PAPER & PLASTIC FILM CAPACITORS IN AC APPLICATIONS (Applicable only to MIL-C-14157 & MIL-C-19978, Chars. E, K, M & Q; MIL-C-39022 all styles).

FIGURE 6.2-2 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR PAPER & PLASTIC FILM CAPACITORS - 85°C MAX RATED (MIL-C-14157,Style CPV17; MIL-C-39022,Style CHR09(50 volt rated), CHR39 & 49; MIL-C-19978,Style CQ08,09,12,13-characteristic M, CQ72-characteristic E, CDR32 & 33)

$$\lambda_p = \lambda_b \ (\Pi_E \ X \ \Pi_Q \ ) \ X \ 10^{-6}$$

λ_b (Base Failure Rate)*

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0055
5	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0033	.0055
10	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0033	.0056
15	.00006	.00006	.00007	.0001	.0002	.0004	.0010	.0019	.0033	.0057
20	.00006	.00006	.00007	.0001	.0002	.0005	.0010	.0019	.0034	.0058
25	.00006	.00006	.00007	.0001	.0002	.0005	.0010	.0019	.0035	.0059
30	.00006	.00006	.00008	.0001	.0002	.0005	.0010	.0020	.0036	.0061
35	.00007	.00007	.00008	.0001	.0002	.0005	.0011	.0021	.0038	.0064
40	.00007	.00007	.00009	.0001	.0002	.0005	.0011	.0022	.0040	.0067
45	.00007	.00008	.00009	.0001	.0002	.0006	.0012	.0024	.0043	.0072
50	.00008	.00008	.0001	.0001	.0003	.0006	.0014	.0026	.0047	.0080
55	.00009	.0001	.0001	.0001	.0003	.0007	.0016	.0030	.0054	.0091
60	.0001	.0001	.0001	.0002	.0004	.0009	.0018	.0035	.0063	.010
65	.0001	.0001	.0001	.0002	.0005	.0011	.0023	.0044	.0078	.0013
70	.0001	.0001	.0002	.0003	.0007	.0015	.0030	.0057	.0010	.0017
75	.0002	.0002	.0003	.0004	.0010	.0021	.0042	.0081	.014	.024
80	.0003	.0003	.0004	.0007	.0015	.0032	.0066	.012	.022	.037
85	.0006	.0006	.0008	.0013	.0027	.0057	.011	.022	.039	.066

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	9
Airborne, Uninhab.	15
Missile, Launch	20

Π_Q (Quality Factor)

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-19978 - Non-ER	10.0

*Observe ac voltage limits of Figure 6.2-1-a and corresponding temperature rise from Figure 6.2-1-b in determining stresses for table look-up.

FIGURE 6.2-3 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR PAPER & PLASTIC FILM CAPACITORS -125°C MAX RATED (MIL-C-39022, Style CHR09 (above 50 volt rated), CHR01, 12, 19, 29 & 59; MIL-C-19978, Style CQ08, 09, 12, 13, 20, 72-characteristic K, CQ06 & 07-characteristic Q, CQR01, 07, 09, 12, 13, 19, 39 & 42)

$$\lambda_p = \lambda_b \ (\Pi_E \ X \ \Pi_Q \ ) \ X \ 10^{-6}$$

λ_b **(Base Failure Rate)***

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0054
5	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0054
10	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0054
15	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0054
20	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0054
25	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0055
30	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0032	.0055
35	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0033	.0055
40	.00006	.00006	.00007	.0001	.0002	.0004	.0009	.0018	.0033	.0056
45	.00006	.00006	.00007	.0001	.0002	.0004	.0010	.0018	.0033	.0056
50	.00006	.00006	.00007	.0001	.0002	.0005	.0010	.0019	.0034	.0057
55	.00006	.00006	.00007	.0001	.0002	.0005	.0010	.0019	.0034	.0058
60	.00006	.00006	.00008	.0001	.0002	.0005	.0010	.0020	.0035	.0060
65	.00006	.00006	.00008	.0001	.0002	.0005	.0010	.0020	.0036	.0061
70	.00007	.00007	.00008	.0001	.0002	.0005	.0011	.0021	.0038	.0064
75	.00007	.00007	.00009	.0001	.0002	.0005	.0011	.0022	.0040	.0067
80	.00007	.00008	.00009	.0001	.0002	.0006	.0012	.0024	.0043	.0072
85	.00008	.00008	.0001	.0001	.0003	.0006	.0013	.0026	.0046	.0078
90	.00009	.00009	.0001	.0001	.0003	.0007	.0015	.0029	.0051	.0087
95	.0001	.0001	.0001	.0002	.0004	.0008	.0017	.0033	.0059	.0099
100	.0001	.0001	.0001	.0002	.0004	.0010	.0020	.0039	.0070	.011
105	.0001	.0001	.0001	.0002	.0005	.0012	.0025	.0048	.0086	.014
110	.0001	.0001	.0002	.0003	.0007	.0016	.0033	.0063	.011	.018
115	.0002	.0002	.0003	.0005	.0010	.0022	.0046	.0088	.015	.026
120	.0004	.0004	.0004	.0008	.0016	.0034	.0070	.013	.023	.039
125	.0006	.0006	.0008	.0013	.0027	.0057	.011	.022	.039	.066

Π_E **(Environment Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	9
Airborne, Uninhab.	15
Missile, Launch	20

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-19978 Non-ER	10.0

*Observe ac voltage limits of Figure 6.2-1-a and corresponding temperature rise from Figure 6.2-1-b in determining stresses for table look-up.

FIGURE 6.2-4 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR MICA CAPACITORS
(MIL-C-5, Style CM(Molded) and MIL-C-39001, Style CMR(Dipped)

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.00004	.00005	.00006	.00008	.0001	.0001	.0002	.0003	.0004	.0006
5	.00005	.00006	.00007	.00009	.0001	.0002	.0003	.0004	.0006	.0008
10	.00006	.00007	.00009	.0001	.0001	.0002	.0003	.0005	.0007	.0010
15	.00007	.00008	.0001	.0001	.0002	.0003	.0004	.0006	.0009	.0012
20	.00009	.0001	.0001	.0001	.0002	.0003	.0005	.0008	.0011	.0014
25	.0001	.0001	.0001	.0002	.0003	.0004	.0006	.0009	.0013	.0018
30	.0001	.0001	.0001	.0002	.0003	.0005	.0008	.0012	.0016	.0022
35	.0001	.0001	.0002	.0003	.0004	.0007	.0010	.0014	.0020	.0027
40	.0002	.0002	.0002	.0004	.0005	.0008	.0012	.0018	.0024	.0033
45	.0002	.0002	.0003	.0004	.0007	.0010	.0015	.0022	.0030	.0040
50	.0003	.0003	.0004	.0006	.0008	.0013	.0019	.0027	.0037	.0049
55	.0003	.0004	.0005	.0007	.0010	.0016	.0023	.0033	.0045	.0061
60	.0004	.0005	.0006	.0008	.0013	.0019	.0028	.0040	.0055	.0074
65	.0005	.0006	.0007	.0010	.0016	.0024	.0034	.0049	.0068	.0091
70	.0006	.0007	.0009	.0013	.0019	.0029	.0042	.0060	.0083	.011
75	.0008	.0009	.0011	.0016	.0024	.0035	.0052	.0073	.010	.013
80	.0010	.0011	.0014	.0020	.0029	.0043	.0063	.0090	.012	.016
85	.0012	.0013	.0017	.0024	.0036	.0053	.0078	.011	.015	.020
90	.0015	.0016	.0021	.0030	.0044	.0065	.0095	.013	.018	.024
95	.0018	.0020	.0026	.0036	.0054	.0080	.011	.016	.022	.030
100	.0022	.0025	.0031	.0044	.0066	.0098	.014	.020	.027	.037
105	.0027	.0030	.0039	.0054	.0081	.012	.017	.024	.033	.045
110	.0034	.0037	.0047	.0067	.0099	.014	.021	.030	.041	.055
115	.0041	.0046	.0058	.0082	.012	.017	.026	.036	.050	.068
120	.0050	.0056	.0071	.010	.014	.021	.031	.045	.062	.083
125	.0062	.0068	.0087	.012	.018	.026	.038	.055	.075	.10

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	4
Airborne, Inhabited	6
Naval, Sheltered	6
Ground, Mobile	6
Naval, Unsheltered	14
Airborne, Uninhab.	24
Missile, Launch	30

Π_Q (Quality Factor)

Failure Rate Level	Π_Q
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-5(molded)	10.0

FIGURE 6.2-5 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR BUTTON MICA CAPACITORS (MIL-C-10950, Style CB)

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.0082	.0091	.0114	.0161	.0238	.0352	.0512	.0724	.0997	.1338
40	.0090	.0100	.0126	.0177	.0261	.0387	.0563	.0797	.1097	.1471
50	.0101	.0111	.0141	.0198	.0292	.0433	.0630	.0891	.1227	.1647
60	.0115	.0127	.0161	.0226	.0334	.0495	.0719	.1018	.1401	.1880
70	.0134	.0149	.0188	.0264	.0390	.0578	.0840	.1188	.1636	.2195
80	.0161	.0178	.0225	.0317	.0467	.0692	.1007	.1424	.1961	.2631
90	.0198	10220	.0278	.0391	.0577	.0855	.1242	.1758	.2421	.3248

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	4
Airborne, Inhabited	6
Naval, Sheltered	6
Ground, Mobile	6
Naval, Unsheltered	17.5
Airborne, Uninhab.	24
Missile, Launch	30

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec	5.0
Lower	15.0

FIGURE 6.2-6 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR GLASS CAPACITORS (MIL-C-23269, Style CYR)

$$\lambda_p = \lambda_b \; (\Pi_E \times \Pi_{CV} \times \Pi_Q) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T ($^\circ$C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0001	.0001	.0002	.0002	.0003	.0005	.0009	.0014	.0022	.0032
5	.0002	.0002	.0002	.0003	.0004	.0007	.0011	.0017	.0027	.0040
10	.0002	.0002	.0003	.0004	.0005	.0008	.0013	.0021	.0033	.0048
15	.0003	.0003	.0003	.0004	.0007	.0010	.0017	.0026	.0040	.0059
20	.0004	.0004	.0004	.0006	.0008	.0013	.0020	.0032	.0049	.0073
25	.0005	.0005	.0005	.0007	.0010	.0016	.0025	.0039	.0060	.0089
30	.0006	.0006	.0007	.0009	.0012	.0019	.0031	.0048	.0073	.010
35	.0007	.0008	.0008	.0011	.0015	.0024	.0038	.0059	.0090	.013
40	.0009	.0009	.0010	.0013	.0019	.0029	.0046	.0072	.011	.016
45	.0011	.0012	.0013	.0016	.0023	.0036	.0056	.0088	.013	.019
50	.0014	.0014	.0016	.0020	.0028	.0044	.0069	.010	.016	.024
55	.0017	.0018	.0019	.0024	.0035	.0054	.0085	.013	.020	.029
60	.0021	.0022	.0024	.0030	.0042	.0066	.010	.016	.024	.036
65	.0026	.0026	.0029	.0037	.0052	.0080	.012	.019	.030	.044
70	.0032	.0032	.0036	.0045	.0064	.0098	.015	.024	.036	.054
75	.0039	.0040	.0044	.0055	.0078	.012	.019	.029	.045	.066
80	.0048	.0049	.0054	.0067	.0096	.014	.023	.036	.055	.081
85	.0058	.0060	.0066	.0082	.011	.018	.028	.044	.067	.099
90	.0071	.0073	.0081	.010	.014	.022	.034	.054	.082	.12
95	.0087	.0090	.0099	.012	.017	.026	.042	.066	.10	.14
100	.010	.011	.012	.015	.021	.032	.051	.081	.12	.18
105	.013	.013	.014	.018	.026	.040	.063	.099	.15	.22
110	.016	.016	.018	.022	.032	.049	.077	.12	.18	.27
115	.019	.020	.022	.027	.039	.060	.094	.14	.22	.33
120	.024	.024	.027	.033	.047	.073	.11	.18	.27	.40
125	.029	.030	.033	.041	.058	.090	.14	.22	.33	.49

Π_{CV} **(Capacitance Factor)**

Capacitance Value in μμf		Π_{CV}
CY10	CY15	
0.5 to 10		0.2
12 to 20	220 to 240	0.4
22 to 30	270 to 360	0.6
33 to 39	390 to 470	0.8
43 to 47	510 to 560	1.0
51 to 100	620 to 680	2.0
110 to 150	750 to 820	3.0
160 to 200	910	4.0
2 0 to 300	1000 to 1200	5.0
CY20	CY30	
560 to 680		0.4
750 to 1000		0.6
1100 to 1300	3600 to 4300	0.8
1500 to 1800	4700 to 5600	1.0
2000 to 3600	6200 to 10000	2.0
3900 to 5100		3.0

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	4
Airborne, Inhabited	6
Naval, Sheltered	6
Ground, Mobile	6
Naval, Unsheltered	14
Airborne, Uninhab.	24
Missile, Launch	30

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03

FIGURE 6.2-7 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR CERAMIC (General Purpose) CAPACITORS - 85°C MAX RATED (MIL-C-11015, 'A' rated temperature; MIL-C-39014, Style CKR13, 48, 64, 72)

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0019	.0024	.0038	.0064	.010	.017	.026	.038	.053	.072
5	.0020	.0025	.0038	.0065	.010	.017	.026	.038	.054	.073
10	.0020	.0025	.0039	.0066	.011	.017	.026	.039	.054	.074
15	.0020	.0025	.0039	.0067	.011	.017	.027	.039	.055	.075
20	.0020	.0026	.0040	.0068	.011	.018	.027	.040	.056	.076
25	.0021	.0026	.0040	.0068	.011	.018	.028	.040	.057	.077
30	.0021	.0026	.0041	.0069	.011	.018	.028	.041	.058	.078
35	.0021	.0027	.0042	.0070	.011	.018	.028	.042	.058	.080
40	.0022	.0027	.0042	.0071	.012	.019	.029	.042	.059	.081
45	.0022	.0028	.0043	.0072	.012	.019	.029	.043	.060	.082
50	.0022	.0028	.0043	.0073	.012	.019	.030	.043	.061	.083
55	.0023	.0028	.0044	.0074	.012	.020	.030	.044	.062	.084
60	.0023	.0029	.0045	.0076	.012	.020	.030	.045	.063	.085
65	.0023	.0029	.0045	.0077	.012	.020	.031	.045	.064	.087
70	.0024	.0030	.0046	.0078	.013	.020	.031	.046	.064	.088
75	.0024	.0030	.0047	.0079	.013	.021	.032	.046	.065	.089
80	.0024	.0030	.0047	.0080	.013	.021	.032	.047	.066	.090
85	.0025	.0031	.0048	.0081	.013	.021	.033	.048	.067	.092

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	8
Airborne, Uninhab.	10
Missile, Launch	15

Π_Q **((Quality Factor)**

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-11015	10.0

FIGURE 6.2-8 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR CERAMIC (General Purpose) - 125°C MAX RATED (MIL-C-11015, 'B' Rated Temperature and MIL-C-39014, Styles CKR05-12, 14-16, 17-19, 73 & 74)

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b **(Base Failure Rate)**

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0018	.0022	.0035	.0059	.0099	.015	.024	.035	.049	.067
5	.0018	.0023	.0035	.0060	.010	.016	.024	.035	.050	.068
10	.0018	.0023	.0036	.0061	.010	.016	.024	.036	.050	.068
15	.0019	.0023	.0036	.0061	.010	.016	.025	.036	.051	.069
20	.0019	.0024	.0037	.0062	.010	.016	.025	.037	.052	.070
25	.0019	.0024	.0037	.0063	.010	.016	.025	.037	.052	.071
30	.0019	.0024	.0038	.0064	.010	.017	.026	.038	.053	.072
35	.0020	.0025	.0038	.0065	.010	.017	.026	.038	.054	.073
40	.0020	.0025	.0039	.0065	.011	.017	.026	.039	.054	.074
45	.0020	.0025	.0039	.0066	.011	.017	.027	.039	.055	.075
50	.0020	.0025	.0040	.0067	.011	.018	.027	.040	.056	.076
55	.0021	.0026	.0040	.0068	.011	.018	.027	.040	.056	.077
60	.0021	.0026	.0041	.0069	.011	.018	.028	.041	.057	.078
65	.0021	.0026	.0041	.0070	.011	.018	.028	.041	.058	.079
70	.0021	.0027	.0042	.0071	.011	.018	.028	.042	.058	.080
75	.0022	.0027	.0042	.0071	.012	.019	.029	.042	.059	.081
80	.0022	.0028	.0043	.0072	.012	.019	.029	.043	.060	.082
85	.0022	.0028	.0043	.0073	.012	.019	.029	.043	.061	.083
90	.0022	.0028	.0044	.0074	.012	.019	.030	.044	.062	.084
95	.0023	.0029	.0044	.0075	.012	.020	.030	.044	.062	.085
100	.0023	.0029	.0045	.0076	.012	.020	.031	.045	.063	.086
105	.0023	.0029	.0046	.0077	.012	.020	.031	.045	.064	.087
110	.0024	.0030	.0046	.0078	.013	.020	.031	.046	.065	.088
115	.0024	.0030	.0047	.0079	.013	.021	.032	.047	.066	.089
120	.0024	.0030	.0047	.0080	.013	.021	.032	.047	.066	.090
125	.0025	.0031	.0048	.0081	.013	.021	.033	.048	.067	.092

Π_E **(Environmental Factor)**

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	8
Airborne, Uninhab.	10
Missile, Launch	15

Π_Q **(Quality Factor)**

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-11015	10.0

FIGURE 6.2-9 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR CERAMIC (General Purpose) - 150°C MAX RATED (MIL-C-11015, 'C' RATED TEMPERATURE)

$$\lambda_p = \lambda_b \left(\pi_E \times \pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0017	.0021	.0033	.0057	.0095	.015	.023	.033	.047	.064
5	.0017	.0022	.0034	.0057	.0096	.015	.023	.034	.048	.065
10	.0018	.0022	.0034	.0058	.0097	.015	.023	.034	.048	.066
15	.0018	.0022	.0035	.0059	.0098	.015	.024	.035	.049	.066
20	.0018	.0023	.0035	.0059	.010	.016	.024	.035	.049	.067
25	.0018	.0023	.0036	.0060	.010	.016	.024	.035	.050	.068
30	.0018	.0023	.0036	.0061	.010	.016	.024	.036	.051	.069
35	.0019	.0023	.0036	.0062	.010	.016	.025	.036	.051	.070
40	.0019	.0024	.0037	.0062	.010	.016	.025	.037	.052	.070
45	.0019	.0024	.0037	.0063	.010	.016	.025	.037	.052	.071
50	.0019	.0024	.0038	.0064	.010	.017	.026	.038	.053	.072
55	.0020	.0025	.0038	.0065	.010	.017	.026	.038	.054	.073
60	.0020	.0025	.0039	.0065	.011	.017	.026	.039	.054	.074
65	.0020	.0025	.0039	.0066	.011	.017	.027	.039	.055	.075
70	.0020	.0025	.0040	.0067	.011	.018	.027	.039	.056	.076
75	.0021	.0026	.0040	.0068	.011	.018	.027	.040	.056	.077
80	.0021	.0026	.0041	.0069	.011	.018	.028	.040	.057	.077
85	.0021	.0026	.0041	.0069	.011	.018	.028	.041	.058	.078
90	.0021	.0027	.0041	.0070	.011	.018	.028	.041	.058	.079
95	.0022	.0027	.0042	.0071	.011	.019	.029	.042	.059	.080
100	.0022	.0027	.0042	.0072	.012	.019	.029	.042	.060	.081
105	.0022	.0028	.0043	.0073	.012	.019	.029	.043	.060	.082
110	.0022	.0028	.0044	.0074	.012	.019	.030	.043	.061	.083
115	.0023	.0028	.0044	.0075	.012	.020	.030	.044	.062	.084
120	.0023	.0029	.0045	.0075	.012	.020	.030	.044	.063	.085
125	.0023	.0029	.0045	.0076	.012	.020	.031	.045	.063	.086
130	.0023	.0029	.0046	.0077	.012	.020	.031	.046	.064	.087
135	.0024	.0030	.0046	.0078	.013	.021	.031	.046	.065	.088
140	.0024	.0030	.0047	.0079	.013	.021	.032	.047	.066	.089
145	.0024	.0030	.0047	.0080	.013	.021	.032	.047	.065	.090
150	.0025	.0031	.0048	.0081	.013	.021	.033	.048	.067	.092

π_E (Environmental Factor)

Environment	π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	8
Airborne, Uninhab.	10
Missile, Launch	15

π_Q (Quality Factor)

Failure Rate Level	π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-11015	10.0

FIGURE 6.2-10 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR CERAMIC, TEMPERATURE COMPENSATING CAPACITORS (MIL-C-20, Style CC)

$$\lambda_p = \lambda_b \ (\Pi_E \ X \ \Pi_Q \ ) \ X \ 10^{-6}$$

λ_b (Base Failure Rate)

T (^{o}C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.00056	.00070	.00108	.00183	.00305	.00488	.00743	.01083	.01519	.02063
5	.00069	.00086	.00132	.00223	.00373	.00596	.00908	.01322	.01855	.02520
35	.00084	.00105	.00162	.00273	.00456	.00728	.01109	.01615	.02266	.03078
40	.00102	.00128	.00198	.00333	.00556	.00889	.01354	.01973	.02767	.03759
45	.00125	.00156	.00241	.00407	.00680	.01086	.01654	.02410	.03380	.04591
50	.00153	.00191	.00295	.00497	.00830	.01327	.02020	.02943	.04128	.05608
55	.00187	.00233	.00360	.00607	.01014	.01621	.02468	.03595	.05042	.06849
60	.00228	.00285	.00440	.00741	.01238	.01979	.03014	.04391	.06158	.08366
65	.00279	.00348	.00537	.00905	.01512	.02418	.03681	.05363	.07522	.10218
70	.00340	.00425	.00656	.01106	.01847	.02953	.04496	.06550	.09187	.12481
75	.00416	.00520	.00802	.01351	.02256	.03607	.05492	.08000	.11221	.15244
80	.00508	.00635	.00979	.01650	.02756	.04405	.06708	.09772	.13706	.18619
85	.00620	.00775	.01196	.02015	.03366	.05381	.08193	.11935	.16740	.22741
90	.00757	.00947	.01460	.02461	.04111	.06572	.10007	.14578	.20447	.27776
95	.00925	.01156	.01784	.03006	.05021	.08027	.12222	.17805	.24974	.33926
100	.01130	.01412	.02179	.03672	.06133	.09804	.14929	.21747	.30503	.41437

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	2
Ground, Fixed	4
Airborne, Inhabited	6
Naval, Sheltered	6
Ground, Mobile	6
Naval, Unsheltered	18
Airborne, Uninhab.	24
Missile, Launch	30

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec	5.0
Lower	15.0

FIGURE 6.2-11 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR TANTALUM ELECTROLYTIC (Solid) CAPACITORS (MIL-C-39003, Style CSR)

$$\lambda_p = \lambda_b \; (\Pi_E \; X \; \Pi_{SR} \; X \; \Pi_Q) \; X \; 10^{-6}$$

λ_b (Base Failure Rate)

T (^oC)	S, Ratio of Operating to Rated Voltage .1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0033	.0036	.0046	.0065	.0096	.014	.020	.029	.040	.054
5	.0033	.0037	.0047	.0066	.0098	.014	.021	.029	.041	.055
10	.0034	.0038	.0048	.0067	.0099	.014	.021	.030	.041	.056
15	.0035	.0038	.0049	.0069	.010	.015	.021	.031	.042	.057
20	.0035	.0039	.0050	.0070	.010	.015	.022	.031	.043	.058
25	.0036	.0040	.0051	.0072	.010	.015	.023	.032	.045	.060
30	.0038	.0042	.0053	.0074	.011	.016	.023	.033	.046	.062
35	.0039	.0043	.0055	.0077	.011	.016	.024	.034	.048	.064
40	.0041	.0045	.0057	.0080	.011	.017	.025	.036	.050	.067
45	.0042	.0047	.0060	.0084	.012	.018	.026	.038	.052	.070
50	.0045	.0050	.0063	.0089	.013	.019	.028	.040	.055	.074
55	.0048	.0053	.0067	.0094	.013	.020	.030	.042	.058	.078
60	.0051	.0056	.0071	.010	.014	.022	.032	.045	.062	.083
65	.0055	.0061	.0077	.010	.016	.023	.034	.049	.067	.090
70	.0060	.0066	.0084	.011	.017	.025	.037	.053	.073	.098
75	.0066	.0073	.0092	.013	.019	.028	.041	.058	.080	.10
80	.0073	.0081	.010	.014	.021	.031	.046	.065	.089	.12
85	.0082	.0091	.011	.016	.024	.035	.051	.073	.10	.13
90	.0095	.011	.013	.019	.028	.041	.059	.084	.12	
95	.011	.012	.015	.022	.032	.047	.069	.097	.13	
100	.013	.014	.018	.026	.038	.056	.081	.12	.16	
105	.016	.017	.022	.031	.045	.067	.097	.14		
110	.019	.021	.027	.038	.056	.082	.12	.17		
115	.024	.027	.034	.047	.070	.10	.15			
120	.031	.034	.043	.061	.090	.13	.19			
125	.041	.045	.057	.080	.12	.18				

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	4
Naval, Sheltered	4
Ground, Mobile	4
Naval, Unsheltered	9
Airborne, Uninhab.	15
Missile, Launch	20

Π_{SR} (Series Resistance Factor)

Circuit Resistance (ohms/volt)	Π_{SR}
≥ 3.0	0.07
2.0	0.10
1.0	0.20
0.8	0.30
0.6	0.40
0.4	0.60
0.2	0.80
0.1	1.0

Π_Q (Quality Factor)

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03

FIGURE 6.2-12 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR TANTALUM ELECTROLYTIC (Non-Solid) CAPACITORS (MIL-C-39006, Style CLR and MIL-C-3965, Style CL)

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0042	.0047	.0059	.008	.012	.018	.026	.037	.051	.069
5	.0043	.0047	.0060	.008	.012	.018	.027	.038	.052	.070
10	.0044	.0048	.0061	.009	.013	.019	.027	.039	.053	.071
15	.0044	.0049	.0062	.009	.013	.019	.028	.039	.054	.073
20	.0046	.0050	.0064	.009	.013	.020	.028	.040	.056	.074
25	.0047	.0052	.0065	.009	.014	.020	.029	.041	.057	.077
30	.0048	.0053	.0068	.009	.014	.021	.030	.043	.059	.079
35	.0050	.0055	.0070	.010	.015	.022	.031	.044	.061	.082
40	.0052	.0058	.0073	.010	.015	.022	.033	.046	.063	.085
45	.0054	.0060	.0076	.011	.016	.023	.034	.048	.066	.089
50	.0057	.0064	.0080	.011	.017	.025	.036	.051	.070	.094
55	.0061	.0067	.0085	.012	.018	.026	.038	.054	.074	.100
60	.0065	.0072	.0091	.013	.019	.028	.041	.058	.079	.106
65	.0070	.0078	.0098	.014	.020	.030	.044	.062	.085	.115
70	.0076	.0084	.0107	.015	.022	.033	.048	.068	.093	.125
75	.0084	.0093	.0117	.016	.024	.036	.052	.074	.102	.137
80	.0093	.0103	.0130	.018	.027	.040	.058	.083	.114	.152
85	.0105	.0116	.0147	.021	.031	.045	.066	.093	.128	.172
90	.0120	.0133	.0168	.024	.035	.052	.075	.106	.146	
95	.0139	.0154	.0195	.027	.040	.060	.087	.123	.170	
100	.0164	.0182	.0230	.032	.048	.071	.103	.145	.200	
105	.0197	.0218	.0276	.039	.057	.085	.123	.175		
110	.0242	.0268	.0339	.048	.070	.104	.152	.214		
115	.0304	.0336	.0425	.060	.088	.131	.190			
120	.0391	.0433	.0547	.077	.114	.168	.245			
125	.0517	.0572	.0723	.102	.150	.223				

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	6
Naval, Sheltered	6
Ground, Mobile	6
Naval, Unsheltered	14
Airborne, Uninhab.	20
Missile, Launch	30

Π_Q (Quality Factor)

Failure Rate Level	Π_Q
L	1.5
M	1.0
P	0.3
R	0.1
S	0.03
MIL-C-3965	10.0

FIGURE 6.2-13 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL
FOR ALUMINUM ELECTROLYTIC CAPACITORS
(MIL-C-39018, Style CU (Aluminum Oxide))

$$\lambda_p = \lambda_b \ (\Pi_E \ X \ \Pi_Q \ ) \ X \ 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0072	.0076	.0086	.010	.014	.019	.026	.036	.048	.064
5	.0077	.0081	.0093	.011	.015	.021	.028	.039	.052	.069
10	.0083	.0088	.010	.012	.016	.022	.031	.042	.056	.074
15	.0091	.0096	.011	.013	.018	.024	.033	.046	.061	.081
20	.010	.010	.012	.015	.019	.027	.037	.050	.067	.089
25	.011	.011	.013	.016	.021	.029	.040	.055	.074	.098
30	.012	.012	.014	.018	.024	.033	.045	.061	.082	.10
35	.013	.014	.016	.020	.027	.037	.050	.069	.092	.12
40	.015	.016	.018	.023	.030	.041	.057	.077	.10	.13
45	.017	.018	.021	.026	.034	.047	.064	.088	.11	.15
50	.019	.021	.024	.029	.039	.054	.074	.10	.13	.17
55	.023	.024	.027	.034	.045	.062	.085	.11	.15	.20
60	.026	.028	.032	.040	.053	.072	.099	.13	.18	.23
65	.031	.033	.038	.047	.062	.085	.11	.15	.21	.28
70	.037	.039	.045	.056	.074	.10	.13	.18	.25	.33
75	.044	.047	.054	.067	.089	.12	.16	.22	.30	.40
80	.054	.057	.065	.081	.10	.14	.20	.27	.36	.48
85	.066	.070	.080	.10	.13	.18	.24	.33	.45	.59
90	.082	.087	.099	.12	.16	.22	.30	.41	.56	
95	.10	.10	.12	.15	.20	.28	.38	.52	.70	
100	.13	.13	.15	.19	.26	.35	.49	.66		
105	.17	.17	.20	.25	.33	.46	.63	.86		
110	.22	.23	.26	.33	.44	.60	.82			
115	.29	.31	.35	.44	.58	.79	1.0			
120	.39	.41	.47	.59	.78	1.0				
125	.54	.57	.65	.81	1.0	1.4				

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	12
Naval, Sheltered	12
Ground, Mobile	12
Naval, Unsheltered	20
Airborne, Uninhab.	30
Missile, Launch	40

Π_Q Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec	3.0
Lower	10.0

FIGURE 6.2-14 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR ALUMINUM DRY ELECTROLYTIC CAPACITORS (MIL-C-62)

$$\lambda_p = \lambda_b \ (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.0096	.0101	.0111	.0133	.0168	.0220	.0294	.0391	.0516	.0672
5	.0106	.0110	.0122	.0146	.0184	.0242	.0322	.0429	.0567	.0738
10	.0017	.0122	.0136	.0161	.0204	.0268	.0357	.0475	.0628	.0817
15	.0131	.0137	.0151	.0180	.0228	.0299	.0399	.0531	.0701	.0914
20	.0148	.0154	.0171	.0204	.0258	.0338	.0450	.0600	.0792	.1031
25	.0169	.0176	.0195	.0232	.0294	.0386	.0514	.0684	.0903	.1176
30	.0195	.0203	.0225	.0268	.0339	.0445	.0592	.0789	.1041	.1357
35	.0227	.0237	.0263	.0313	.0396	.0519	.0692	.0921	.1216	.1584
40	.0269	.0280	.0311	.0370	.0468	.0614	.0818	.1089	.1438	.1873
45	.0322	.0336	.0372	.0444	.0561	.0736	.0981	.1306	.1724	.2246
50	.0392	.0408	.0453	.0540	.0682	.0895	.1193	.1589	.2097	.2732
55	.0484	.0504	.0559	.0666	.0843	.1106	.1474	.1963	.2590	.3374
60	.0608	.0633	.0702	.0837	.1058	.1389	.1850	.2464	.3253	.4237
65	.0777	.0809	.0898	.1069	.1352	.1775	.2364	.3149	.4156	.5414
70	.1011	.1053	.1168	.1392	.1760	.2310	.3077	.4098	.5409	.7046
75	.1342	.1398	.1550	.1847	.2336	.3066	.4084	.5439	.7179	.9351
80	.1818	.1894	.2100	.2505	.3165	.4153	.5533	.7369	.9726	1.2669
65	.2517	.2623	.2908	.3465	.4382	.5751	.7661	1.0203	1.3467	1.7543

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Airborne, Inhabited	12
Naval, Sheltered	12
Ground, Mobile	12
Naval, Unsheltered	20
Airborne, Uninhab.	30
Missile, Launch	40

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec	3.0
Lower	10.0

FIGURE 6.2-15 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR VARIABLE CERAMIC CAPACITOR (MIL-C-81)

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
25	.0023	.0051	.0125	.0270	.0509	.0865	.1362	.2024	.2874	.3935
30	.0024	.0053	.0131	.0282	.0532	.0905	.1426	.2118	.3008	.4118
35	.0026	.0056	.0138	.0298	.0561	.0955	.1503	.2234	.3171	.4342
40	.0027	.0059	.0147	.0317	.0597	.1015	.1598	.2375	.3372	.4617
45	.0029	.0064	.0157	.0340	.0641	.1090	.1716	.2549	.3620	.4956
50	.0032	.0069	.0171	.0369	.0695	.1182	.1862	.2767	.3928	.5379
55	.0035	.0076	.0188	.0405	.0764	.1299	.2046	.3040	.4316	.5910
60	.0039	.0085	.0209	.0452	.0851	.1448	.2280	.3388	.4810	.6586
65	.0044	.0096	.0237	.0511	.0964	.1639	.2581	.3835	.5445	.7456
70	.0051	.0110	.0273	.0589	.1111	.1889	.2975	.4420	.6276	.8593
75	.0059	.0130	.0321	.0693	.1306	.2222	.3499	.5198	.7380	1.0106
80	.0072	.0156	.0386	.0834	.1572	.2672	.4209	.6253	.8878	1.2156
85	.0088	.0193	.0476	.1029	.1939	.3297	.5193	.7715	1.0954	1.4999
90	.0112	.0245	.0605	.1306	.2462	.4186	.6592	.9795	1.3906	1.9041
95	.0147	.0321	.0793	.1711	.3226	.5486	.8640	1.2837	1.8226	2.4956
100	.0199	.0436	.1076	.2324	.4382	.7451	1.1734	1.7434	2.4752	3.3892

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	
Ground, Fixed	4
Airborne, Inhabited	8
Naval, Sheltered	8
Ground, Mobile	8
Naval, Unsheltered	24
Airborne, Uninhab.	50
Missile, Launch	70

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec	4.0
Lower	20.0

FIGURE 6.2-16 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR VARIABLE, PISTON TYPE (Tubular Trimmer) CAPACITOR (MIL-C-14409)

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_Q) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	S, Ratio of Operating to Rated Voltage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
30	.0146	.0173	.0249	.0395	.0635	.0995	.1496	.2163	.3020	.4090
40	.0197	.0235	.0336	.0534	.0860	.1347	.2026	.2929	.4089	.5538
50	.0267	.0318	.0456	.0723	.1165	.1824	.2743	.3966	.5537	.7498
60	.0362	.0431	.0617	.0979	.1577	.2469	.3714	.5370	.7497	1.0152
70	.0490	.0583	.0835	.1326	.2135	.3343	.5028	.7271	1.0150	1.3746
80	.0664	.0789	.1131	.1795	.2891	.4526	.6808	.9844	1.3743	1.8611
90	.0898	.1069	.1531	.2431	.3915	.6128	.9218	1.3328	1.8607	2.5199
100	.1217	.1447	.2073	.3291	.5300	.8297	1.2480	1.8046	2.5193	3.4118
110	.1647	.1947	.2806	.4456	.7177	1.1234	1.6898	2.4434	3.4110	4.6195
120	.2230	.2653	.3800	.6034	.9717	1.5211	2.2879	3.3082	4.6184	6.2546
130	.3019	.3592	.5145	.8169	1.3156	2.0595	3.0977	4.4792	6.2531	8.4684
140	.4088	.4863	.6966	1.1061	1.7813	2.7885	4.1941	6.0646	8.4664	11.4658
150	.5535	.6584	.9432	1.4976	2.4118	3.7754	5.6786	8.2112	11.4631	15.5242

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	.1
Space Flight	.1
Ground, Fixed	.3
Airborne, Inhabited	1.0
Naval, Sheltered	1.0
Ground, Mobile	1.0
Naval, Unsheltered	5.0
Airborne, Uninhab.	8.0
Missile, Launch	12.0

Π_Q (Quality Factor)

Quality Level	Π_Q
Upper	1.0
Mil-Spec	3.0
Lower	10.0

TABLE 6.2-2
CAPACITOR BASE FAILURE RATE (λ_b) FACTORS

Style	MIL-C-SPEC	A	B	N_T	G	N_S	H	FIGURE NOS. λ_b
CB	10950	$8.9(10)^{-4}$	1	358	1	.3	3	6.2-5
CC	20	$3.6(10)^{-9}$	1	25	1	.3	3	6.2-10
CE	62	$4.2(10)^{-3}$	1	282	5.9	.55	3	6.2-14
CHR	39022	$5.5(10)^{-5}$	2.5	358	18	.4	5	6.2-2
CHR	39022	$5.5(10)^{-5}$	2.5	398	18	.4	5	6.2-3
CK	11015 Max Rated T=85°C	$8.9(10)^{-4}$	1	358	1	.3	3	6.2-7
	Max Rated T=125°C	$8.9(10)^{-4}$		398	1	.3	3	6.2-8
	Max Rated T=150°C	$8.9(10)^{-4}$	1	423	1	.3	3	6.2-9
CKR	39014	See Style CK.						
CL	3965	$3.8(10)^{-3}$	1	358	9	.4	3	6.2-12
CLR	39006	See Style CL.						
CM	5	$6.9(10)^{-10}$	16	398	1	.4	3	6.2-4
CMR	39001	$6.9(10)^{-10}$	16	398	1	.4	3	6.2-4
CPV	14157	$5.5(10)^{-5}$	2.5	338	18	.4	5	6.2-1
CPV	14157	$5.5(10)^{-5}$	2.5	358	18	.4	5	6.2-2
CPV	14157	$5.5(10)^{-5}$	2.5	398	18	.4	5	6.2-3
CQ & CQR	19978	See Style CPV.						
CSR	39003	$3(10)^{-3}$	1	358	9	.4	3	6.2-11
CU	39018	$3.3(10)^{-3}$	3	358	5	.5	3	6.2-13
CV	81	$1.5(10)^{-3}$	1	342	10.1	.17	3	6.2-15
CYR	23269	$3.3(10)^{-9}$	16	398	1	.5	4	6.2-6
PC	14409	$1.46(10)^{-6}$	1	33	1	.33	3	6.2-16

6.3 Operational/Non-Operational Failure Rate Comparison

Table 6.3-1 presents the operational failure rates and the operating to non-operating failure rate ratio. The operating failure rates were calculated using the MIL-HDBK-217B prediction models assuming the following factors:

For paper, mica, glass and ceramic capacitors, a voltage derating of 50 percent was assumed for a quality level 'M' part at 25°C.

For tantalum capacitors, a 50 percent voltage derating was assumed for a quality level 'M' part with 0.1 ohms per volt circuit resistance.

For aluminum electrolytic capacitors, a voltage derating of 50 percent for an upper quality level part was assumed.

For variable piston type capacitors, a 50 percent voltage derating was assumed for an upper quality level part at 25°C.

The comparison between operational and non-operational shows a higher failure rate in storage for paper, plastic and mica capacitors.

Missile launch ratios were obtained directly from MIL-HDBK-217B.

TABLE 6.3-1. CAPACITOR OPERATING AND NON-OPERATING FACTORS

DEVICE CATEGORY CAPACITORS	NON-OPERATING FAILURE RATE x 10^{-9}	GROUND, FIXED, OPERATING FAILURE RATE x 10^{-9}	G.F.-OPERATING TO NON-OPERATING RATIO	MISSILE LAUNCH TO G.F.-OPERATING RATIO
Paper & Plastic				
CQ	4.10	6.0	1.5	10
CPV & CQR	1.11	0.06	0.05	10
Mica				
CM	<0.38	32.0	84.2	10
CB	<0.38	580.0	1526.0	8
CMR	<0.38	0.32	0.84	10
Glass				
MIL-STD	<0.81	11.0	13.6	10
CYR	<0.81	1.1	1.4	10
Ceramic				
CC & CK	2.14	220.0	102.8	8
CKR	0.32	2.2	6.9	8
Solid Tantalum				
CSR	0.13	2.6	20.0	10
Non-Solid Tantalum				
CL	12.5	340.0	27.2	16
CLR	8.98	3.4	0.38	16
Aluminum Oxide				
CU	<6.46	230.0	35.6	23
Variable, Piston				
PC	<5.65	110.0	19.5	45

7.0 Inductive Devices

Inductive devices refer to a wide category of components dependent upon a number of turns of wire designed to oppose a change in current flow in an electric circuit, to produce magnetic flux or to react mechanically to a changing magnetic flux.

The three most common inductive devices are coils (inductors), transformers and inductive filters.

A coil is simply several turns of wire around a supporting structure. Since inductive operation depends on the physical spiral arrangements of the wire, provisions are taken to prevent contact between adjacent wire turns. This is accomplished by insulating the wire. Potting the entire device also provides insulation and provides additional mechanical strength.

A transformer is a device consisting of two or more coils coupled together by magnetic induction. Its main components are input and output coils and a core around which the coils are wound. As in the case of the simple coil, the wire turns in the input and output coils must be insulated from each other.

An inductive filter is a network which purpose is to selectively block or allow passage of certain frequencies or band of frequencies. It is comprised of several coils in network form mounted on a supporting structure such as a printed circuit board or any other suitable means. In its basic form the common RF choke can be considered the simplest form of inductive filter.

Transformers and inductors are classified in accordance to their intended use by MIL-T-27A. The specification lists six grades of transformers and inductors. Each grade is intended for use as indicated in Table 7.0-1.

Most transformer and inductor failures consist of breakdown of insulating material. Therefore, selection of insulating material is of paramount importance. Insulating material has been classified in accordance with their temperature characteristics in AIEE Standard No. 1. This classification is shown in Table 7.0-2.

TABLE 7.0-1. MIL-T-27A TRANSFORMERS AND INDUCTORS CLASSIFIED BY GRADE

GRADE	INTENDED USE
1	Where maximum reliability, life, or operation under all climatic conditions is required.
2	Where flame resistance is required in addition to the requirements of Grade 1.
3	Where little or no protection from climatic conditions is required.
4	Where extreme resistance to shock and vibration is required in addition to the requirements of Grade 1.
5	Where resistance to flame is required in addition to the requirements of Grades 1 and 4.
6	Where little or no protection from climatic conditions is required but where extreme resistance to shock and vibration is needed.

A cross reference between AIEE Standard No. 1 and MIL-T-27 is shown in Table 7.0-3.

TABLE 7.0-3. COMPARISON OF INSULATING MATERIALS DEFINED BY AIEE STANDARD NO. 1 AND MIL-T-27A*

HOTSPOT TEMP (°C)	AIEE Designation	MIL-T-27A Designation
85	-	Q*
90	O	-
105	A	R
130	B	S
170	-	T
180	H	-
170	-	U
No limit specified	C	-

* Applicable to MIL-T-27 Grades 1 and 4 only.

TABLE 7.0-2

TEMPERATURE CLASSIFICATION OF INSULATING MATERIALS IN ACCORDANCE WITH AIEE STANDARD NO. 1

CLASS	DESCRIPTION OF MATERIAL	HOTSPOT TEMP (°C)
O	Consists of cotton, silk, paper, and similar organic materials when neither impregnated* nor immersed in a liquid dielectric	90
A	Consists of: (1) cotton, silk, paper, and similar organic materials when either impregnated* or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolic resins, and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) varnishes (enamel) as applied to conductors	105
B	Consists of mica, asbestos, fiberglass, and similar inorganic materials in built-up form with organic binding substances. A small proportion of Class A materials may be used for structural purposes only**	130
H	Consists of (1) mica, asbestos, fiberglass and similar inorganic materials in built-up form with binding substances composed of silicone compounds in rubbery or resinous forms, or materials with equivalent properties. A minute proportion of Class A materials may be used only when essential for structural purposes during manufacture***	180
C	Consists entirely of mica, porcelain, glass, quartz, and similar inorganic materials	No limit selected

*An insulation is considered to be "impregnated" when a suitable substance replaces the air between its fibers, even if this substance does not completely fill the spaces between the insulated conductors. The impregnating substances, in order to be considered suitable, must have good insulating properties; must entirely cover the fibers, and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause; must not flow during the operation of the machine at full working load nor at the temperature limit specified; and must not unduly deteriorate under prolonged action of heat.

**The electrical and mechanical properties of the insulated winding must not be impaired by application of the temperature permitted for Class B material. (The word "impaired" is here used in the sense of causing any change that could disqualify the insulating material for continuous service.) The temperature endurance of different Class B insulation assemblies varies over a considerable range in accordance with the percentage of Class A materials employed and the degree of dependence placed on the organic binder for maintaining the structural

TABLE 7.0-2 (cont'd)

integrity of the insulation.

***The electrical and mechanical properties of the insulated winding shall not be impaired by the application of the temperature permitted for Class H material. (The word "impaired" is here used in the sense of causing any change that could disqualify the insulating material for continuous service.)

7.1 Storage Reliability Analysis

7.1.1 Failure Modes

The most common failure mode for inductive devices are shorts and opens. Shorts usually are the result of breakdown of insulation. During operation, breakdown of insulation is normally the result of over voltage and current developing hot spots. This leads to embrittlement and degradation resulting in ultimate breakdown. During storage, this is the result of chemical changes and deterioration accelerated by temperature, humidity and reactions with atmosphere gases.

Opens are associated with breakage of fine winding wire. Unless caused by mechanical shock or stresses opens are normally associated with manufacturing problems such as stress in relief loops, wire nicks, and soldering of lead wires to the windings.

Failure modes are also accelerated by use conditions. The effects of various use and storage conditions on coils and transformers are summarized in Table 7.1-1.

Table 7.1-1 . FAILURE MODES AFFECTED BY VARIOUS USE AND STORAGE CONDITIONS

Component	Vibration Effects	Shock Effects	Temperature Effects	Humidity Effects	Salt Spray Effects	Storage Effects
Transformers	Shorts: opens; modulation of output	Shorts; opens; modulation of output	Reduced dielectric; opens; shorts; hot spots; malformation	Corrosion; fungus; shorts; opens	Corrosion; shorts; opens	Deterioration of potting and dielectric
Coils	Loss of sensitivity; detuning; breaking of parts, leads, and connectors	Lead breakage; detuning; loss of sensitivity	Warping, melting; instability; change in dielectric properties	Electrolysis; corrosion	Corrosion; electrolysis	

7.1.2 Non-Operational Failure Rate Predictions

The non-operational failure rates for the four types of components analyzed are shown in Table 7.1-2.

TABLE 7.1-2. INDUCTIVE DEVICES NON-OPERATIONAL FAILURE RATES

	MIL-STD		HI-REL	
DEVICE TYPE	λ x 10^{-9}	90% CL x 10^{-9}	λ x 10^{-9}	90% CL x 10^{-9}
Filters & Chokes	9.62	37.4	.55	1.47
Coils	<1.34	3.1	1.11	2.95
Transformers	13.9	21.9	.91	2.01
Reactors	<76.9	177.7	3.12	12.1

7.1.3 Non-Operating Failure Rate Data

The data base on inductive devices included over 10.5 billion storage part hours from seven different sources.

Missile D data (Table 7.1-3) consists of 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes 246 million inductive device storage hours with no failures. All of the devices in missile D are rated Hi-Rel.

Missile E-1 data (Table 7.1-4) consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included nearly one billion part hours without a single failure. All of the devices in missile E-1 are rated MIL-STD.

Missile F data (Table 7.1-5) consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southwest desert under open side metal roof sheds (12 feet high); 30 missiles stored outside in the canal zone under open side metal roof sheds (12 feet high); and 30 missiles stored in the southeast U. S. in bunkers. The data includes 18 million inductive device storage hours with no failures. All of the devices in missile F are rated Hi-Rel.

Missile G data (Table 7.1-6) consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southwest desert; 12 missiles stored outside in the noftheast U. S.; 12 missiles stored on the Gulf coast; and 23 missiles stored in bunkers in the southeast U. S. The data includes 12 million inductive device storage hours with no failures. All of the devices in Missile G are rated Hi-Rel.

Missile H data (Table 7.1-7) represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. For 1,071 missiles, storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. Almost 4.5 billion part hours were reported by this source with four failures. All of the devices in this missile are rated Hi-Rel.

Missile I data (Table 7.1-8) consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the world. The data includes 618 million inductive device storage hours with 1 failure recorded for a reactor. All of the devices in Missile I are rated Hi-Rel.

Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual sources. The data for source A is summarized in Table 7.1-9. Both MIL-STD and HI-REL devices were included.

The sources identified six types of devices: filters, chokes, coils, transformers, inductors and reactors. Since an RF choke is a simple filter, the data on these two devices were combined. Inductors and coils are basically different names for the same device, therefore these data were combined.

Statistical tests were then employed to determine the feasibility of combining the data from the different sources. These tests, presented in Appendix A, test the likelihood that the failure rates from different sources come from the same population. If the tests are positive, it is most likely that the failure rates belong to the same population and hence the data may be combined to form a single failure rate. If the tests are negative, the failure rates are most likely from different populations and should not be combined.

For each device type, the tests proved positive. The data from the different sources was pooled together for each quality grade (MIL-STD, Hi-Rel).

TABLE 7.1-3.

MISSILE D NON-OPERATING DATA FOR INDUCTIVE DEVICES (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HRS. x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Coil, RF	9699	118.094	0	< 8.47
Transformer, Power	1431	17.424	0	<57.4
Transformer, RF	5406	65.823	0	<15.2
Transformer, AF	795	9.680	0	<103.3
Transformer, Pulse	1749	21.296	0	<47.0
Reactor	1113	13.552	0	<73.8

TABLE 7.1-4

MISSILE E-1 NON-OPERATING DATA FOR INDUCTIVE DEVICES (MIL-STD)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Filters				
General Class	5244	76.562	0	(<13.1)
Coils				
RF	34086	497.656	0	(<2.0)
Toroidal	1748	25.521	0	(<39.2)
IF	5244	76.562	0	(<13.1)
Transformers				
Reference	5244	76.562	0	(<13.1)
Audio	1748	25.521	0	(<39.2)
Power	874	12.760	0	(<78.4)
Signal	1748	25.521	0	(<39.2)
Inductors				
General Class	1748	25.521	0	(<39.2)
RF	7866	114.844	0	(<8.7)
Reactors	874	12.760	0	(<78.4)

TABLE 7.1-5

MISSILE F NON-OPERATING DATA FOR INDUCTIVE DEVICES (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Reactor	8586	15.768	0	(<63.4)
Transformer, AF	120	2.628	0	(<380.5)

TABLE 7.1-6

MISSILE G NON-OPERATING DATA FOR INDUCTIVE DEVICES (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Reactor	312	8.947	0	<111.8
Filter, RF	78	2.237	0	<447.2
Transformer, AF	39	1.118	0	<894.5

TABLE 7.1-7

MISSILE H NON-OPERATING DATA FOR INDUCTIVE DEVICES (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS $\times 10^6$	NUMBER FAILED	FAILURE RATE IN FITS
Filters				
General Class	220626	3505.0	2	0.57
Coils				
General Class	46053	731.6	2*	2.73
Transformers				
General Class	13923	221.2	0	(<4.52)
Reactors	1071	17.0	0	(<58.8)

*Failure mode was unsoldered connection inside coil.

TABLE 7.1-8

MISSILE I NON-OPERATING DATA FOR INDUCTIVE DEVICES (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS $\times 10^6$	NUMBER FAILED	FAILURE RATE IN FITS
Coil	33120	329.44	0	<3.03
Reactor	24840	247.08	1	4.05
Transformer	4140	41.18	0	<24.28

TABLE 7.1-9. SOURCE A NON-OPERATING DATA FOR INDUCTIVE DEVICES

DEVICE TYPE	MIL-STD			HI-REL		
	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS	STORAGE HOURS x 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Filters						
General Class	-	-	-	88.488	0	(<11.3)
Ceramic Bandpass	.126	0	(<7936.)	-	-	-
Ceramic Feedthrough	.378	1	2645.	-	-	-
Transmittal	.378	0	(<2645.)	-	-	-
RC, Low Pass	25.704	0	(<38.9)	-	-	-
EMI	-	-	-	10.044	0	(<99.6)
Chokes	.756	0	(<1323.)	9.437	0	(<106.)
Coils						
General Class	-	-	-	79.181	0	(<12.6)
RF	5.418	0	(<185.)	285.800	0	(<3.5)
Transformers	509.000	9	17.7	2928.309	3	1.0
Inductors	-	-	-	261.557	0	(<3.8)
Reactors	-	-	-	18.8	0	(<53.2)

TABLE 7.1-10

INDUCTIVE DEVICES STORAGE FAILURE RATES & CONFIDENCE LIMITS

DEVICE TYPE	STORAGE HRS. x 10^6	FAILURES	λ x 10^{-9}	90% CL x 10^{-9}
	MIL-STD			
Filters & Chokes	104	1	9.62	37.4
Coils	746	0	(<1.34)	3.10
Transformers	649	9	13.87	21.9
Reactors	13	0	(<76.9)	177.7
	HI-REL			
Filters & Chokes	3615	2	0.55	1.47
Coils	1806	2	1.11	2.95
Transformers	3309	3	0.91	2.01
Reactors	321	1	3.12	12.1

7.2 Inductive Devices Operational Prediction Models

The MIL-HDBK-217B general failure rate model for inductive devices is:

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_f) \times 10^{-6}$$

where: λ_p = device failure rate

λ_b = base failure rate

Π_E = Environmental factor

Π_f = family type factor

Specific model parameter values are given in Figure 7.2-1 for MIL-T-27 Transformers and Inductors (Audio, Power and HiPower Pulse) and MIL-C-15305 Radio Frequency Coils; and in Figure 7.2-2 for MIL-T-21038 Low Power Pulse Transformers.

The base failure rate and adjustment factor values presented in the figures are based on certain assumptions. See sections 7.2.1 and 7.2.2 for a description of these parameters.

7.2.1 Base Failure Rate (λ_b)

The equation for the base failure rate, λ_b, is:

$$\lambda_b = Ae^x \text{ where } x = \left(\frac{T_{HS} + 273}{N_T}\right)^G$$

T_{HS} = Hot stop temperature in degrees C, e is natural logarithm base, 2718,

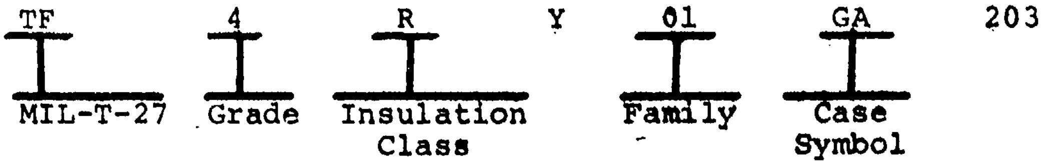
A, N_T, and G are model equation constants

The determination of hot spot temperature is described in Section 7.2.3.

The model equation constants are given in Tables 7.2-1 and 7.2-3. The models are valid only if T_{HS} is not above the temperature rating for a given insultation class.

Devices in accordance with the three specifications included in this section are identified by the classification scheme used in each specification. The following information will help in determining the Insultation Class, the Family Type and the Construction Grade if only the specification and type designation are known:

a. MIL-T-27. An example type designation per this specification is



The Grade and Insulation Class symbols are the same as used in Figures 7.2-1 and 7.2-2. The codes used for Family Type are

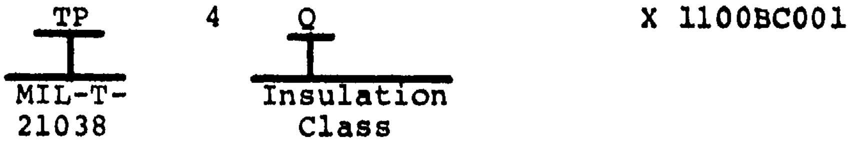
Power transformer + filter: 01 thru 09, 37, thru 41
Audio transformer: 10 thru 21, 50 thru 53
Pulse transformer: 22 thru 36, 54

b. MIL-C-15305. All parts in this specification are r.f. coils. An example type designation is

The codes used for the Insulation Class are

Class B: 4, 5, 6
Class 0: 7, 8, 9
Class A: 10, 11, 12

c. MIL-T-21038. All parts in this specification are pulse transformers. An example type designation is



The Insulation Class symbols are the same as used in Figures 7.2-1 and 7.2-2.

7.2.2 Π Adjustment Factor

7.2.2.1 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in the Appendix.

Grade 6 transformers require adequate environmental protection through encapsulation, or sealing; otherwise, application in any of these environments is unacceptable, and values not valid.

TABLE 7.2-1.

MODEL EQUATION CONSTANTS, MIL-T-27 INSULATION CLASS & MAX OPERATING TEMP. (MIL-C-15305 Class in Parenthesis)

Insulation Class

Constants	Q (O) 85°C	R (A) 105°C	S (B) 130°C	V* 155°C	T* 170°C	U* >170°C
A	6.37×10^{-4}	7.20×10^{-4}	6.06×10^{-4}	1.83×10^{-3}	2.03×10^{-3}	2.6×10^{-3}
N_T	329	352	364	409	398	477
G	15.6	14.0	8.7	10.0	3.8	8.4

* Temperature ratings for these "letters" are different from Table 7.2-2.

TABLE 7.2-2.

MODEL EQUATION CONSTANTS, MIL-T-21038 INSULATION CLASS & MAX OPERATION TEMPERATURE

Insulation Class

Constants	Q 85°C	R 105°C	S 130°C	T* 155°C	U* 170°C	V* >170°C
A	6.37×10^{-4}	7.20×10^{-4}	6.06×10^{-4}	1.83×10^{-3}	2.03×10^{-3}	2.6×10^{-3}
N_T	329	352	364	409	398	477
G	15.6	14.0	8.7	10.0	3.8	8.4

* Temperature ratings for these "letters" are different from Table 7.2-1.

FIGURE 7.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR MIL-T-27, TRANSFORMERS AND INDUCTORS (AUDIO, POWER & HI POWER PULSE) AND MIL-C-15305, COILS, RADIO"FREQUENCY

$$\lambda_p = \lambda_b (\Pi_E \times \Pi_f) \times 10^{-6}$$

MIL-T-27, Base Failure Rate, λ_b** (MIL-C-15305 Class in Parenthese)

T_{HS}	Q(O) 85°C	R(A) 105°C	S(B) 130°C	V* 155°C	T* 170°C	U* >170°C	T_{HS}	R(A) 105°C	S(B) 130°C	V* 155°C	T* 170°C	U* >170°C
0	.0007	.0007	.0007	.0019	.0026	.0026	95	.0046	.0018	.0026	.0042	.0029
5	.0007	.0008	.0007	.0019	.0026	.0026	100	.0068	.0021	.0027	.0044	.0030
10	.0007	.0008	.0007	.0019	.0027	.0026	105	.0108	.0024	.0029	.0046	.0030
15	.0007	.0008	.0007	.0019	.0027	.0026	110		.0029	.0031	.0048	.0031
20	.0008	.0008	.0007	.0019	.0028	.0026	115		.0035	.0033	.0050	.0031
25	.0008	.0008	.0007	.0019	.0028	.0027	120		.0042	.0036	.0053	.0032
30	.0008	.0008	.0007	.0019	.0029	.0027	125		.0053	.0040	.0056	.0032
35	.0009	.0008	.0008	.0019	.0030	.0027	130		.0068	.0043	.0058	.0033
40	.0010	.0009	.0008	.0020	.0030	.0027	135			.0049	.0061	.0034
45	.0012	.0009	.0008	.0020	.0031	.0027	140			.0055	.0064	.0035
50	.0014	.0010	.0009	.0020	.0032	.0027	145			.0063	.0068	.0036
55	.0017	.0010	.0009	.0020	.0033	.0027	150			.0074	.0072	.0037
60	.0021	.0011	.0009	.0021	.0034	.0027	155			.0088	.0076	.0039
65	.0029	.0013	.0010	.0021	.0035	.0028	160				.0081	.0041
70	.0043	.0014	.0011	.0022	.0036	.0028	165				.0086	.0042
75	.0070	.0017	.0012	.0022	.0037	.0028	170				.0091	.0045
80	.0128	.0020	.0013	.0023	.0038	.0028	175					.0047
85	.0267	.0026	.0014	.0024	.0040	.0028	180					.0050
90		.0034	.0016	.0025	.0041	.0029	185					.0053

*-Temperature ratings for these "letters" are different from Figure 7.2-2.

**-If there is no λ_b for a given T_{HS} and Class, device is over-rated.

Π_F(Family Type Factor)

Family Type	Upper	Mil-Spec	Lower
Pulse Transformers	1.0	1.5	5.0
Audio Transformers	1.5	3.0	7.5
Power Transformers and Filters	4.0	8.0	20.0
RF Transformers and Coils	6.0	12.0	30.0

Π_E(Environment Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Ground, Mobile	3
Airborne, Inhab.	5
Naval	5
Airborne, Uninhab.	7
Missile, Launch	10

FIGURE 7.2-2 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR MIL-T-21038, TRANSFORMERS, PULSE, LOW POWER

$$\lambda_p = \lambda_b \left(\Pi_E \times \Pi_f \right) \times 10^{-6}$$

λ_b (Base Failure Rate for MIL-T-21038)**

T_{HS}	Q 85°C	R 105°C	S 130°C	T* 155°C	U* 170°C	V* >170°C	T_{HS}	R 105°C	S 130°C	T* 155°C	U* 170°C	V* >170°C
0	.0007	.0007	.0007	.0019	.0026	.0026	95	.0046	.0018	.0026	.0043	.0029
5	.0007	.0008	.0007	.0019	.0026	.0026	100	.0068	.0021	.0027	.0044	.0030
10	.0007	.0008	.0007	.0019	.0027	.0026	105	.0108	.0024	.0029	.0046	.0030
15	.0007	.0008	.0007	.0019	.0027	.0026	110		.0029	.0031	.0048	.0031
20	.0008	.0008	.0007	.0019	.0028	.0026	115		.0035	.0033	.0050	.0031
25	.0008	.0008	.0007	.0019	.0028	.0027	120		.0042	.0036	.0053	.0032
30	.0008	.0008	.0007	.0019	.0029	.0027	125		.0053	.0039	.0055	.0032
35	.0009	.0008	.0008	.0019	.0030	.0027	130		.0068	.0043	.0058	.0033
40	.0010	.0009	.0008	.0020	.0030	.0027	135			.0049	.0061	.0034
45	.0012	.0009	.0008	.0020	.0031	.0027	140			.0055	.0064	.0035
50	.0013	.0010	.0009	.0020	.0032	.0027	145			.0063	.0068	.0036
55	.0017	.0010	.0009	.0020	.0033	.0027	150			.0074	.0072	.0037
60	.0021	.0011	.0010	.0021	.0034	.0027	155			.0088	.0076	.0039
65	.0029	.0013	.0010	.0021	.0035	.0028	160				.0081	.0041
70	.0043	.0014	.0011	.0022	.0036	.0028	165				.0086	.0042
75	.0070	.0017	.0012	.0022	.0037	.0028	170				.0091	.0045
80	.0128	.0020	.0013	.0023	.0038	.0028	175					.0047
85	.0267	.0026	.0014	.0024	.0040	.0028	180					.0050
90		.0034	.0016	.0025	.0041	.0029	185					.0053

*-Temperature ratings for these "letters" are different from Figure 7.2-1.
**-If there is no λ_b shown for a given T_{HS} & Class, device is over-rated.

Π_F (Family Type Factor)

Family Type	Upper	Mil-Spec	Lower
Pulse Transformers	1.0	1.5	5.0
Audio Transformers	1.5	3.0	7.5
Power Transformers and Filters	4.0	8.0	20.0
RF Transformers and Coils	6.0	12.0	30.0

Π_E (Environment Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Ground, Mobile	3
Airborne, Inhab.	5
Naval	5
Airborne, Uninhab.	7
Missile, Launch	10

7.2.3 Hot Spot Temperature

The failure rate, λ_p, of the inductive device is a function of the hot spot temperature of the inductive device. This hot spot temperature can be obtained by direct measurement or by approximation. Although the latter method is normally used, there may be times when the direct measurement technique would be advisable.

7.2.3.1 Determination of Hot Spot Temperature - Direct Measurement

a) Average Temperature Rise, Change in Resistance Method as described in MIL-T-27 (4.8.14) or MIL-T-21038 (4.7.14)

$$\Delta T = \frac{R - r}{r}(t + 234.5) - (T - t)$$

where

ΔT = Temperature rise in degrees Centigrade above specified maximum ambient temperature

R = resistance of winding in ohms at temperature $(T + \Delta T)$

r = resistance of winding in ohms at temperature (t)

t = specified initial ambient temperature in degrees Centigrade

T = maximum ambient temperature in degrees Centigrade (at time of power shutoff); T shall not differ from t by more than 5°C.

For transformers, rated voltage shall be applied to the primary with the specified loads across the secondaries. For inductors, rated d-c and a-c, current shall be applied to the windings.

b) Hot Spot Temperature Rise

Approximate value by assuming temperature-rise of hot spot is 10 percent greater than highest average temperature-rise as measured or as estimated by approximate methods. See para. 7.2.3.2.

Actual measurement requires burying of thermocouples or thermistors in coils; hence is not feasible to measure on complete part. However, for developmental devices, this step should be seriously considered where temperature is significant.

7.2.3.2 Determination of Hot Spot Temperature - Approximation

Approximation of the hot spot temperature can be determined by referring to Figures 7.2-3 through 7.2-6, which gives the average temperature rise. Use the figure which best correlates to the known input data. If Figure 7.2-4 is used to determine the temperature, use of a MIL-T-20138 transformer, case AF will give the most practical result. The hot spot temperature is then calculated as follows:

$$T_{HS} = T_A + 1.1\ (\ T)$$

T_{HS} = Hot spot temperature (C°)

T_A = ambient temperature (C°)

ΔT = temperature rise (C°)

When using Figures 7.2-3 through 7.2-6, it is advisable to follow the order of precedence established via Table 7.2-3.

TABLE 7.2-3

ESTIMATE OF AVERAGE TEMPERATURE-RISE*

Reference	Input Data	To Calculate Approximate Average Temperature-Rise**	Comment
Figure 7.2-3 (Step 1A)	Power loss (watts) Radiating surface area of case (sq in.)	Enter graph with radiating area on ordinate; locate intersection with appropriate line for power loss and read temperature-rise on abscissa.	Radiating area readings include heat losses due to both radiation and convection. This method preferred for MIL-T-21038 & MIL-C-15305.
Figure 7.2-4 (Step 1B)	Power loss (watts) Case symbol per MIL-T-27	Enter graph with case symbol on ordinate; locate intersection with appropriate line for power loss and read temperature-rise on abscissa.	Case symbols represent standard case sizes.
Figure 7.2-5 (Step 1C)	Power loss (watts) Transformer weight (lb)	Enter graph with weight on abscissa; locate intersections with appropriate line for power and loss and read temperature-rise on ordinate.	This calculation is possible because of actual relationship between size and weight of conventional transformers.
Figure 7.2-6 (Step 1D)	Power input (watts) Transformer weight (lb) Assumed 80 percent efficiency	Enter graph with weight on abscissa; locate intersection with appropriate line for power input and read probable temperature-rise on ordinate.	Note error possibility in efficiency assumption; use Figure 7.2-3, and 7.2-5 preferably.

*Hot-Spot Temperature = Ambient Air Temperature plus 1.1 times average temperature rise (or measured coil temperature).

**Graphs give predicted temperature rise in still air and in absence of nearby heat radiation from other components; if forced air cooling or heat radiation is used, it is preferable to measure transformer temperature [illegible] making conditions. Measure power loss or input at normal use frequency.

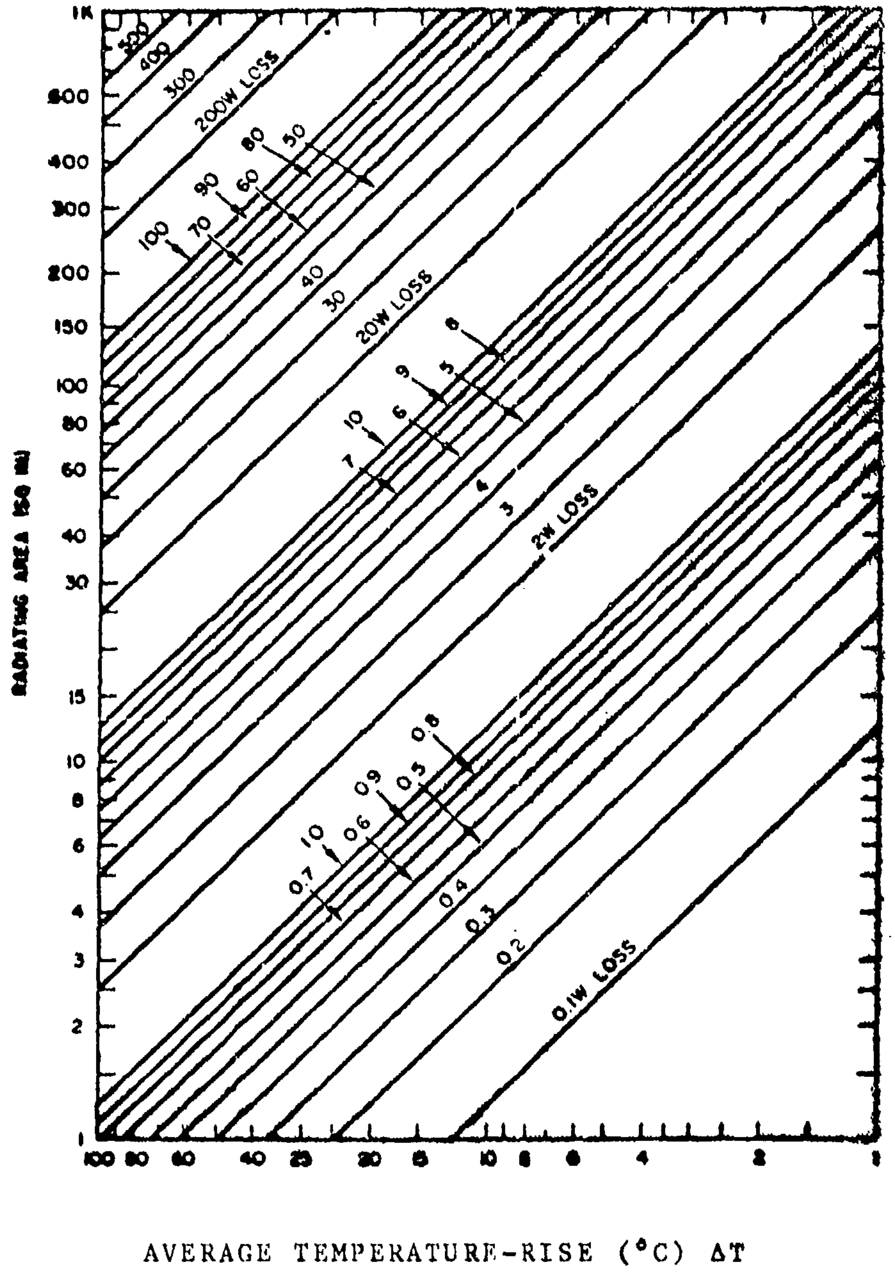
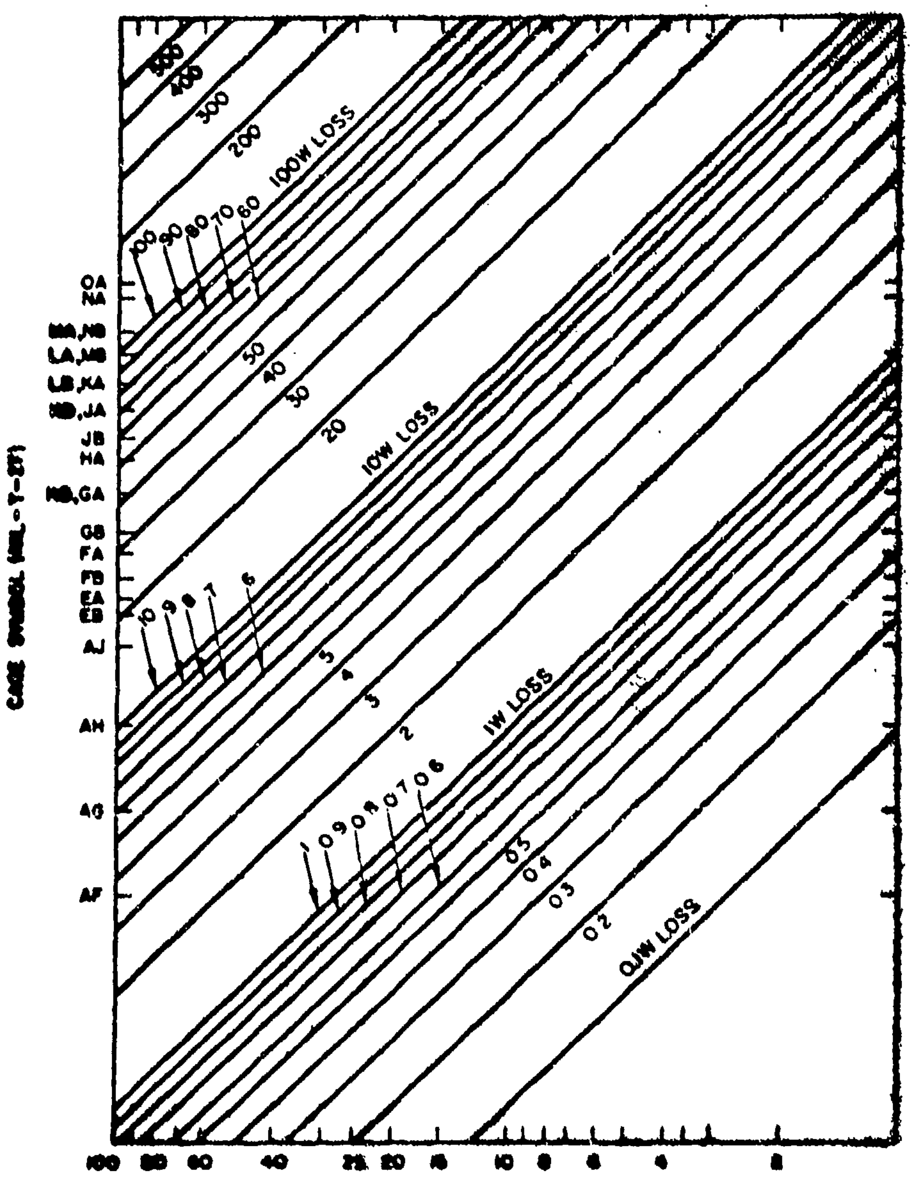


FIGURE 7.2-3. POWER LOSS AND RADIATING AREA KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Step 1A)



AVERAGE TEMPERATURE-RISE (°C), ΔT

FIGURE 7.2-4. POWER LOSS AND CASE SYMBOL KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Step 1B)

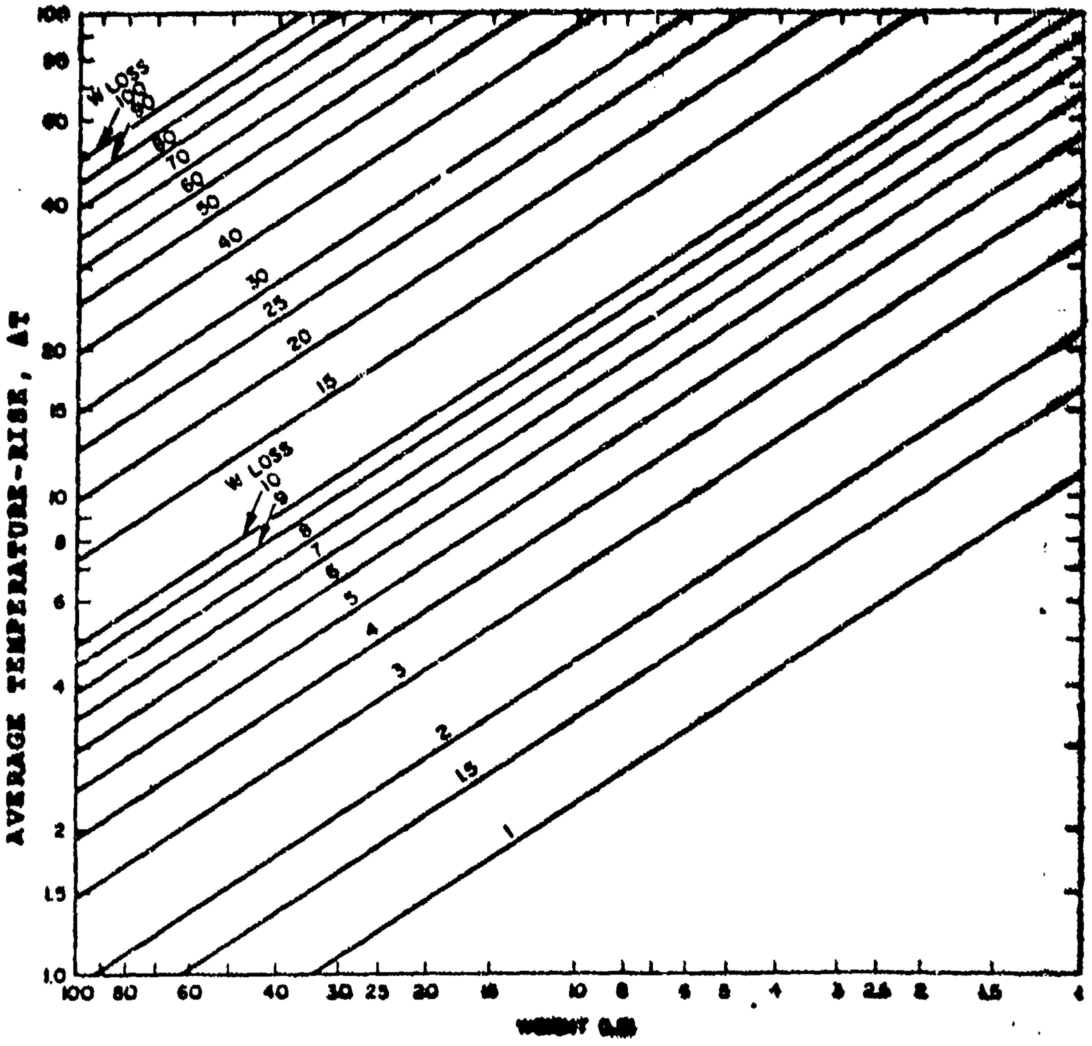


FIGURE 7.2-5. POWER LOSS AND WEIGHT KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Step 1C)

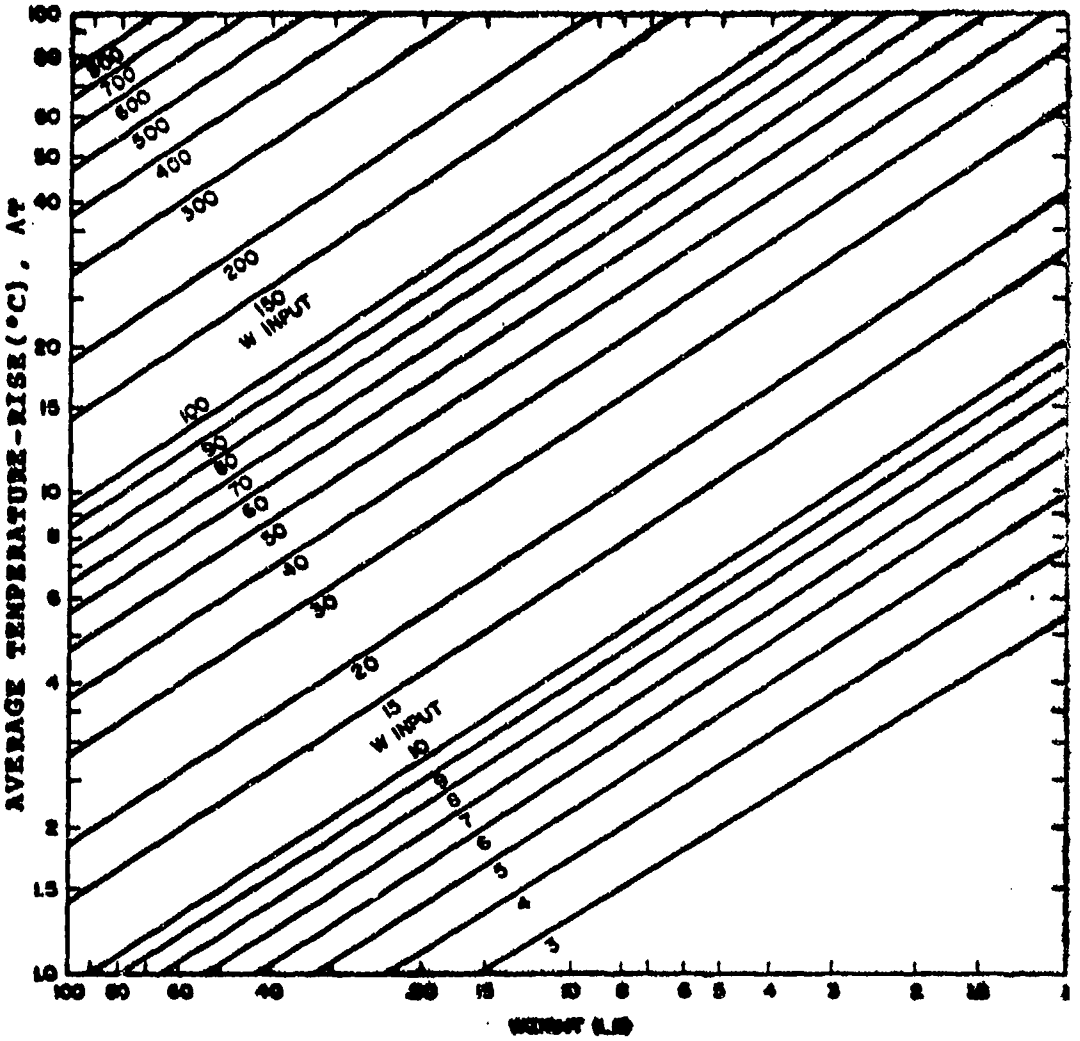


FIGURE 7.2-6. POWER INPUT AND WEIGHT KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Based on 80 PERCENT EFFICIENCY) (Step 1D)

7.3 Operational/Non-Operational Failure Rate Comparison

Operational to non-operational failure rate ratios have been computed for comparison purposes. Non-operational failure rates were derived in Section 7.1. Operational failure rates were computed using the models in Section 7.2 with the following assumptions:

a) For coils, a hot spot temperature of 20°C was assumed.

b) For transformers, insulation Class "Q" and a temperature rise of 20°C were assumed.

Failure rate comparisons are summarized in Table 7.3-1.

TABLE 7.3-1. OPERATING TO NON-OPERATING FAILURE RATE RATIO

DEVICE CATEGORY	NON-OPERATING $\lambda \times 10^{-9}$	GROUND, FIXED OPER. $\lambda \times 10^{-9}$	OPERATING TO NON-OPERATING λ RATIO
Hi-Rel			
Filters	0.55	9.6	17.5
Coils	1.11	6.4	5.8
Transformers	0.91	9.6	10.5
Reactors	3.12	6.4	2.1
MIL-STD			
Filters	9.62	12.8	1.3
Coils	<1.34	19.2	14.3
Transformers	<13.9	19.2	1.4
Reactors	<76.9	19.2	0.25

7.4 Conclusions

Compared to other devices, inductive components have low failure rates. Therefore, they do not represent potential reliability problems in missile systems.

Hi-Rel filters and transformers show a 10 to 1 improvement in storage failure rate over MIL-STD devices. Coils did not show a great difference between Hi-Rel and MIL-STD in spite of the fact that the data base for MIL-STD coils did not contain a single failure and therefore the failure rate quoted represents a worst case situation.

8.0 Crystals

This section contains reliability information and analysis on crystals. Available information did not specify crystal material, therefore the failure rate must be considered only under the general classification of crystals.

8.1 Storage Reliability Analysis

8.1.1 Non-Operational Failure Rate

The non-operational failure rate for crystals was estimated at 39.3 failures per billion hours.

8.1.2 Non-Operational Failure Data

Approximately one hundred million storage hours for crystals with four failures were reported from four sources (Table 8.1-1).

TABLE 8.1-1 NON-OPERATING DATA FOR CRYSTALS

SOURCE	NO. OF DEVICES	STORAGE HRS. x 10^6	FAILURES	NON-OPERATING FAILURE RATE IN FITS
Missile D	795	9.680	0	<103.31
Missile H	3213	51.0	4	78.43
Missile I	2070	20.98	0	<47.66
Source A		20.065	0	<49.84
TOTAL		101.725	4	39.3 (78.6 fits - 90% one sided confidence level)

Missile D data consists of 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes 9.68 million crystal storage hours with no failures.

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time.

No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. Fifty one million crystal storage hours were reported by this source with four failures.

Missile I data consists of 2070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the world. The data includes 21 million crystal storage hours with no failures recorded.

Source A represents a reliability study performed under contract to RADC. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual sources. The data includes 20 million crystal storage hours with no failures.

8.2 Operational Failure Rate Information

The operational failure rate for quartz crystals is listed in MIL-HDBK-217B as 0.2 failures per million hours.

8.3 Operational/Non-Operational Failure Rate Comparison

Operational to non-operational failure rate ratio for crystals is 5 based on the above failure rates.

9.0 Miscellaneous Electrical Devices

Table 9.0-1 lists non-operating data and failure rates for a number of electrical devices. The operating failure rates were extracted from MIL-HDBK-217B.

TABLE 9.0-1 MISCELLANEOUS ELECTRICAL DEVICES NON-OPERATING AND OPERATING FAILURE RATES

SOURCE	DEVICE	NON-OP. HRS.x 10^6	NO. FAIL	NON-OP. FAIL. RATE IN FITS	OP. FAIL. RATE IN FITS	RATIO OP. TO NON-OP.
A	Flight Inst. Missile	264.0	25	94.7	10000.	106
A	Spark Gap	7.3	0	(<137.0)	-	-
A	Fuses	2.1	0	(<476.2)		
Missile F	Fuse, Fast Acting	2.6	0	(<384.6)		
	Fuses, Total	4.7	0	(<212.8)	100.	-
A	Heaters	2.6	0	(<384.6)	1000.	-
A	Magnetic Core	35799.1	0	(<.028)	-	-
A	Soler Cells	748.6	8	10.7	-	-
A	Temp. Sensor	.2	0	(<5000.)		
Missile D	Temp. Sensor	1.9	0	(<526.3)		
	Total Temp. Sensors	2.1	0	(<476.2)	-	-
A	Lamp, Annunciator	.7	0	(<1428.6)	-	-
A	Lamp, Electroluminescant	27.3	1	36.6	-	-
A	Lamp, Incandescant	9.5	1	105.3	1000.	9.5
Missile F	Lamp, Short Arc	2.6	0	(<384.6)	200.	-
Missile E-1	Lamp, Neon	12.8	0	(<78.1)	200.	-

10.0 Connectors and Connections

10.1 Storage Reliability Analysis

10.1.1 Failure Modes

In joints of good design and good workmanship, possible failure modes are those due to handling, to fatigue, and to corrosion. Corrosion and fatigue due to temperature changes are probably the dominant failure mechanisms in storage.

10.1.2 Non-Operating Failure Rate Prediction

The non-operating failure rate for all types of permanent connections in high reliability equipment is 0.012 failures per billion hours.

10.1.3 Non-Operating Failure Rate Data

The non-operating failure rate data analyzed is shown in Table 10.1-1, 10.1-2 and 10.1-3.

Pin connector data (Table 10.1-1) consists of 82 billion connector storage hours with one failure recorded. Solder joint connection data (Table 10.1-2) consists of 35 billion connection storage hours with no failures recorded. The miscellaneous connection data in Table 10.1-3 contains 17 billion storage hours with 17 failures recorded. No details are available from the data source showing 17 failures. A statistical test (see Appendix A) indicates that the miscellaneous data set is most likely not from the same population data as those in Tables 10.1-1 and 10.1-2.

Since no failures are shown for solder connections, the predicted non-operating failure rate for permanent connections is based solely on the pin connector data.

The following describes the data sources:

Source A is a data collection effort sponsored by RADC and documented in Report No. RADC-TR-74-269, "Effects of Dormancy on Nonelectronic Components and Materiels," Oct. 1974. No details of storage conditions, etc. are available for this data.

TABLE 10.1-1. PIN CONNECTORS NON-OPERATING DATA

SOURCE	NO. OF DEVICES	TOTAL STORAGE HRS. $\times 10^6$	NO. OF FAILURES	λ IN FITS
A	-	163.	0	<6.13
B	-	47.4	0	<21.1
C	-	79861.0	0	<.013
Missile E-1	23598	344.541	1	2.90
Missile G	117	3.354	0	<298.2
Missile H	127449	2024.7	0	<0.49
	TOTAL	82443.995	1	.012

(λ = .047 fits at 90% one-sided confidence level)

TABLE 10.1-2. SOLDER CONNECTIONS NON-OPERATING DATA

SOURCE	TOTAL STORAGE HRS. $\times 10^6$	NO. OF FAILURES	λ IN FITS
A	169	0	<5.92
B	316	0	<3.16
C	34900	0	<.029
TOTAL	35385	0	<.028

(λ = .065 fits at 90% one-sided confidence level)

TABLE 10.1-3. MISC. CONNECTORS & CONNECTIONS NON-OPERATING DATA

TYPE	SOURCE	TOTAL STORAGE HRS. $\times 10^6$	NO. OF FAILURES	λ IN FITS
Stud & Nut	A	24.5	0	<40.8
Welded	B	5580.	0	<0.18
General	C	11603.	17	1.47
Submarine-Gen.	C	6.3	0	<158.73
	TOTAL	17213.8	17	0.99

(λ = 1.37 fits at 90% one-sided confidence level)

Source B is data from dormant operation of spacecraft, Report AD 889943, "Reliability Data from In-flight Spacecraft; 1958-1970" E. E. Bean and C. E. Bloomquist, 30 Nov. 1971.

Source C is an early data collection effort sponsored by RADC: Report No. RADC-TR-68-114, "Data Collection for Nonelectronic Reliability Handbook," June 1968. No details of environments, etc. are available for this data.

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included nearly three hundred and fifty million connector hours with one failure. All of the devices in missile E-1 are rated MIL-STD.

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. The data includes three million connector storage hours with no failures.

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. The data includes two billion connector storage hours with no failures reported.

10.2 Connector and Connection Operational Prediction Models

10.2.1 Connectors

The MIL-HDBK-217B general failure rate model for a mating pair of connectors is:

$$\lambda_p = [\lambda_b (\Pi_E \times \Pi_p) + N\lambda_{cyc}] \times 10^{-6}$$

where: λ_p = device failure rate
λ_b = base failure rate
Π_E = Environmental Adjustment Factor
Π_p = Pin Quantity Adjustment Factor
N = Number of active pins
λ_{cyc} = Cycling Rate Factor

The term containing λ_{cyc} may be ignored for connectors experiencing cycling rates ≤ 40 cycles/1000 hr. Figure 10.2-1 gives the connector model and parameter values. Use of the model requires identification of insert materiel. Table 10.2-1 lists insert materiels classifications for the various types of connectors and Table 10.2-2 identifies these insert materiel classifications and the temperature ranges.

The base failure rate and adjustment factor values presented in Figure 10.2-1 are based on certain assumptions. See Sections 10.2.1 and 10.2.2 for a description of these parameters.

10.2.1.1 Base Failure Rate (λ_b)

The equation for the base failure rate λ_b is:

$$\lambda_b = A\,e^x$$

$$\text{where}\quad x = \left(\frac{T + 273}{N_T}\right)^G + \left(\frac{T + 273}{T_O}\right)^P$$

e = 2.718, natural logarithm base
T = operating temperature (°C).
= ambient + temp. rise (See Table 10.2-4).

A, T_O, N_T, G and P are model constants (See Table 10.2-3).

FIGURE 10.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR CONNECTORS

$$\lambda_p = [\lambda_b (\Pi_E \times \Pi_p) + N\lambda_{cyc}] \times 10^{-6}$$

λ_b (Base Failure Rate)

T	Insert Material*			
(°C)	A	B	C	D
0	.0010	.004	.034	.060
10	.0012	.005	.043	.077
20	.0015	.007	.053	.098
30	.0019	.009	.065	.125
40	.0022	.012	.078	.158
50	.0027	.015	.095	.200
60	.0032	.019	.116	.254
70	.0037	.024	.139	.323
80	.0044	.030	.170	.413
90	.0051	.037	.209	.530
100	.0060	.046	.257	.687
110	.0070	.058	.316	
120	.0082	.072	.393	
130	.0095	.089		
140	.0111	.111		
150	.0130	.139		
160	.0153	.175		
170	.0180	.221		
180	.0213	.281		
190	.0254	.359		
200	.0304	.463		
210	.0367			
220	.0447			
230	.0549			
240	.0682			
250	.0857			

Π_E (Environmental Factor)*

Environment	MIL-SPEC	Lower Quality
Ground, Benign	1(1)	10(10)
Space Flight	1(1)	10(10)
Ground, Fixed	4(4)	16(16)
Airborne, Inhabited	4(6)	15(24)
Naval, Sheltered	4(6)	12(36)
Ground, Mobile	8(8)	16(16)
Naval, Unsheltered	9(9)	19(19)
Airborne, Uninhab.	10(10)	20(20)
Missile, Launch	15(15)	30(30)

*-Values in Parenthesis are for coaxial connectors.

Π_p (Factor for number of Active Contacts)

N*	Π_p	N*	Π_p	N*	Π_p	N*	Π_p
1	1.00	15	3.28	65	13.20	135	43.08
2	1.36	16	3.42	70	14.60	140	46.25
3	1.55	17	3.57	75	16.10	145	49.60
4	1.72	18	3.71	80	17.69	150	53.12
5	1.87	19	3.86	85	10.39	155	56.83
6	2.02	20	4.00	90	21.19	160	60.74
7	2.16	25	4.78	95	23.10	165	64.85
8	2.30	30	5.60	100	25.13	170	69.17
9	2.44	35	6.46	105	27.28	175	73.70
10	2.58	40	7.42	110	29.56	180	78.47
11	2.72	45	8.42	115	31.98	185	83.47
12	2.86	50	9.50	120	34.53	190	88.72
13	3.00	55	10.65	125	37.22	195	94.23
14	3.14	60	11.89	130	40.07	200	100.0

*- N = Number of active contacts.

λ_{cyc} (Cycling Rate Factor)

f*	λ_{cyc}	f	λ_{cyc}
10	.0011	260	.0135
20	.0012	270	.0149
30	.0013	280	.0164
40	.0015	290	.0182
50	.0016	300	.0201
60	.0018	310	.0222
70	.0020	320	.0245
80	.0022	330	.0271
90	.0025	340	.0300
100	.0027	350	.0331
110	.0030	360	.0366
120	.0033	370	.0404
130	.0037	380	.0447
140	.0041	390	.0494
150	.0045	400	.0546
160	.0050	410	.0603
170	.0055	420	.0667
180	.0060	430	.0737
190	.0067	440	.0815
200	.0074	450	.0900
210	.0082	460	.0995
220	.0090	470	.1099
230	.0100	480	.1215
240	.0110	490	.1343
250	.0122	500	.1484

*f = rate in cycles/1000hrs.

*For λ_b, if a mating pair of connectors uses two types of insert material, use the average of the base failure rates for the two insert types.

TABLE 10.2-1. CONFIGURATION, APPLICABLE SPECIFICATION, AND INSERT MATERIAL FOR CONNECTORS

Configuration	Specification	Insert Material (see Table 10.2-2)			
		A	B	C	D
Rack and Panel	MIL-C-28748		X		
	MIL-C-83733		X		
	MIL-C-24308	X	X		
Printed Wiring Board	MIL-C-21097		X		
	MIL-C-55302		X		
Cable, Circular	MIL-C-5015		X		X
	MIL-C-26482	X	X		X
	MIL-C-38999	X	X		
	MIL-C-81511		X		
	MIL-C-83723		X		
Power	MIL-C-3767				X
Coaxial, RF	MIL-C-3607			X	
	MIL-C-3643			X	
	MIL-C-3650			X	
	MIL-C-3655			X	
	MIL-C-25516			X	
	MIL-C-39012			X	

TABLE 10.2-2. TEMPERATURE RANGES OF INSERT MATERIALS

Type	Common Insert Materials	Temperature Range, °C *
A	Vitreous Glass, Alumina Ceramic, Polyimide	-55 to 250
B	Diallyl Phthalate, Melamine, Fluorosilicone, Silicone Rubber, Polysulfone, Epoxy Resin	-55 to 200
C	Polytetrafluoroethylene (Teflon) Chlorotrifluoroethylene (Kel-F)	-55 to 125
D	Polyamide (Nylon), Polychloroprene (Neoprene), Polyethylene	-55 to 125

* These temperature ranges indicate maximum capability of the insert material alone. Connectors using these materials generally have a reduced temperature range caused by other considerations of connector design. See applicable connector specification for connector operating temperature range.

TABLE 10.2-3. MODEL CONSTANTS

Constants	Insert Material (see tables 10.2-1 and 10.2-2)			
	A	B	C	D
A	0.324	6.9	3.06	12.3
T_O	473	423	373	358
N_T	-1592	-2073.6	-1298	-1528.8
G	-1	-1	-1	-1
P	5.36	4.66	4.25	4.72

TABLE 10.2-4. INSERT TEMPERATURE RISE (°C) vs. CONTACT CURRENT & CONTACT SIZE

AMPERES PER CONTACT	CONTACT SIZE 22 Ga.	20 Ga.	16 Ga.	12 Ga.
2	3.7	2.4	1.0	0.4
3	7.7	5.0	2.2	0.8
4	13.	8.5	3.7	1.4
5	20.	13.	5.5	2.0
6	27.	18.	7.7	2.8
7	36.	24.	10.	3.7
8	46.	30.	13.	4.8
9	58.	37.	16.	5.9
10	70.	45.	20.	7.2
15		95.	41.	15.
20			70.	25.
25			105.	38.
30				53.
35				71.
40				91.

NOTE: 1: $\Delta T = .989(i)^{1.85}$ for 22 gauge.
$\Delta T = .64(i)^{1.85}$ for 20 gauge.
$\Delta T = .274(i)^{1.85}$ for 16 gauge.
$\Delta T = 0.1(i)^{1.85}$ for 12 gauge.

ΔT = °C insert temperature rise.
i = amperes per contact

NOTE 2: The operating temperature of the connector is usually assumed to be the sum of the ambient temperature surrounding the connector plus the temperature rise generated in the contact. If the connector is mounted on a suitable heat sink (hot or cold plate), the temperature of this sink is usually taken as the ambient. For those circuit design conditions which generate a contact hot spot, this hot-spot temperature rise is added to the ambient to obtain the operating temperature.)

10.2.1.2 Adjustment Factors

10.2.1.2.1 Environmental Adjustment Factor, Π_E

Π_E accounts for the influence of environmental factors other than temperature. Refer to the environment description in the Appendix.

10.2.1.2.2 Pin Quantity Adjustment Factor, Π_P

Π_P accounts for the quantity of contacts. For coaxial and triaxial connectors, etc., the shield contact is counted as an active pin.

$$\Pi_P = e^{\left(\frac{N-1}{N_O}\right)^q}$$

where $N_O = 10$

$q = 0.51064$

N = Number of active pins

10.2.1.2.3 Cycling Rate Factor, λ_{cyc}

λ_{cyc} adjusts the model for cycling rates. The term is ignored for connectors experiencing cycling rates $\leq$ 40 cycles/1000 hr.

The values for λ_{cyc} are derived from the following equation:

$$\lambda_{cyc} = .001\, e^{(f/100)}$$

where f is the cycling rate in cycles/1000 hrs.

10.2.2 Connections

The MIL-HDBK-217B failure rate predictions for solder, crimp, weld and wire wrap connections are presented in Figure 10.2-2.

FIGURE 10.2-2. CONNECTIONS OPERATIONAL FAILURE RATE PREDICTIONS

Connections	λ_p (10^{-6}/hr.)
Solder, reflow lap to P.C. boards	0.00012
Solder, wave to P.C. boards	0.00044
Other hand solder connections (e.g., wire to terminal board)	0.0044
Crimp	0.0073
Weld	0.002
Wirewrap	0.0000037

10.3 Operational/Non-Operational Failure Rate Comparisons

Using the model in Section 10.2, the operational failure rate is estimated at .09 failures per million hours under the following assumptions.

a) Configuration and insert material-printed wiring board
b) Operating temperature - 30°C
c) Number of pins - 20
d) Operating environment - ground fixed
e) Cycles - less than 40 cycles per 1000 hours.

The non-operating failure rate for pin connectors in Section 10.1 was .012 fit. The operational to non-operational failure rate ratio is 7500.

11.0 Printed Wiring Boards

11.1 Storage Reliability Analysis

11.1.1 Failure Mechanisms

Printed circuits have a dominant failure mechanism which imposes a definite limitation on life. It is caused by the difference in the thermal coefficient of expansion of the substrate and the plated copper. The copper yields to accomodate temperature changes, but eventually a fatigue failure causes an open circuit, usually in one of the plated thru holes. Use of very pure copper and control of the cross section help to extend the life.

Research results show that over 200 cycles from -65° to 110°C are obtainable, 50 cycles on a test coupon of 80 or more holes is recommended as a screening test.

11.1.2 Non-Operational Failure Rate

Non-operational failure rate of printed wiring boards is estimated at .67 failures per billion hours.

11.1.3 Non-Operational Data

Non-operational data collected consisted of approximately 3 billion hours with two failures reported (Table 11.1-1).

TABLE 11.1-1

NON-OPERATING DATA IN PRINTED WIRING BOARDS

SOURCE	NO. OF DEVICES	STORAGE HRS. $\times 10^6$	FAILURES	STORAGE FAILURE RATE IN FITS
Missile D	5565	67.759	1	1.48
Missile F	1200	26.280	1	3.81
Missile G	156	4.473	0	<223.6
Missile H	161721	2569.2	0	<.389
Missile I	31050	308.85	0	<3.24
TOTALS		2976.562	2	0.67 (1.79 fits - 90% one-sided confidence level)

Missile D data consists of 159 missiles stored for periods from one month up to 62 months for an average storage period of 17 months. The missile storage was environmentally controlled and periodic checkouts were performed. The data includes approximately 68 million printed wiring board storage hours with one failure reported. The failure mode was listed as open.

Missile F data consists of 120 missiles, 60 of which were stored for one year and 60 for two years. The missiles in storage containers experienced the following environments: 30 missiles stored outside in the Arctic on wooden racks with canvas covers; 30 missiles stored outside in the southeast desert under open sided metal roof sheds; 30 missiles stored outside in the canal zone under open sided metal roof sheds; and 30 missiles stored in the southeast U. S. in bunkers. The data includes four and a half million printed wiring board storage hours with one failure reported. The failure was recorded in the missiles stored in the Arctic with the failure mode listed as salt contamination.

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. The data includes four and a half million printed wiring board storage hours with no failures.

Missile H data represents field data from a recent army missile program fielded in the 1970's. The major item in which the devices were assembled was subjected to operating times at high and low temperatures, shock and vibration. The missiles were transported overseas and stored for various lengths of time. No tests were run until the missiles were removed from storage and returned to the states. Storage durations varied from 6 months to 6 years with an average time of 1.8 years. Storage environments included cannister time in a controlled environment, cannister time subject to outside elements and missile time on pallets and on launchers. A number of samples were also run through road tests under field conditions. The data includes two and a half billion printed wiring board storage hours with one failure reported.

Missile I data consists of 2.070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. The data includes more than 300 million printed wiring board storage hours with no failures reported.

11.2 Printed Wiring Boards Operational Prediction Model

The MIL-HDBK-217B failure rate model for MIL-P-55110 Printed Wiring Boards and MIL-P-55640 Multilayer (Plated-Through-Hole) Printed Wiring Boards is

$$\lambda_p = \lambda_b N \Pi_E \times 10^{-6}$$

where: λ_p = board failure rate
λ_b = base failure rate
N = number of plated-through holes
Π_E = Environmental Adjustment Factor

The above model is applicable only to high quality boards that have received screening and burn-in and that use G-10 or equivalent epoxy materials.

Figure 11.2-1 gives the specific values for the model. See the Appendix for a description of the environments.

FIGURE 11.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR PRINTED WIRING BOARDS

$$\lambda_p = \lambda_b N \Pi_E \times 10^{-6}$$

λ_b (Base Failure Rate)

Type	λ_b
Two-Sided Boards	6×10^{-6}
Multi-layer Boards	5×10^{-4}

N = Number of Plated Through Holes.

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	1
Space Flight	1
Ground, Fixed	2
Naval, Sheltered	4
Ground, Mobile	4
Airborne, Inhabited	6
Naval, Unsheltered	10
Airborne, Uninhab.	20
Missile, Launch	20

11.3 Operational/Non-Operational Failure Rate Comparison

Using the model in Section 11.2, the operational failure rate of a multilayer board with 100 holes in a ground environment is 100 failures per billion hours. The operational to non-operational failure rate ratio is 149.

11.4 Conclusions and Recommendations

Fatigue failure due to thermal cycling is the dominant failure mechanism. A coupon is taken from the printed circuit board to use in verifying the quality of the plated thru holes.

Constant temperature storage would be ideal. Lacking that, it is desirable to limit both the frequency and amplitude of the temperature excursions.

Some studies on matching the expansion coefficients have been made.

In application of printed circuit boards, cracking of solder joints is also a problem. The problem is more severe if encapsulating or potting are used. The principle design process for alleviating this problem is stress relief.

APPENDIX A

TEST OF SIGNIFICANCE OF DIFFERENCES IN FAILURE RATES (MORE THAN TWO POPULATIONS)

The storage reliability data is obtained from numerous sources. A detailed qualitative analysis is performed on the data to classify devices, environments, uses, quality levels, failures modes & mechanisms, and so on. Once the data sets are grouped according to these analyses, it is still not certain whether grouped sets of failure data are in truth from the same statistical population. It is possible that the failure rate characteristics of identical devices from the same manufacturers, with the same application, use environment, and so on, are not from the same population in terms of reliability -- possibly due to some problem on a production line for a certain lot or other factor.

Therefore a statistical test is performed to determine if the different data sets could be from the same statistical population.

The technique used is for more than two data sets and is taken from "Statistical Methods for Research Workers," R. A. Fisher, 13th edition, Hufner, 1963, pages 99-101.

The techniques assumes that the underlying failure distributions each have the same constant failure rate (λ). Therefore, the probability of a number of failures for each population can be represented by the Poisson distribution.

A single failure rate is calculated based on the pooled data sets being tested.

$$\lambda = \frac{\sum_{i=1}^{N} f_i}{\sum_{i=1}^{N} T_i}$$

where λ = Mean failure rate for all data sets

f_i = the number of failures in data set i

T_i = the total storage hours in data set i

n = the number of data sets being tested

The expected number of failures and the difference between the expected number of failures and actual failures is calculated for each data set based on the pooled data:

$$M_i = \lambda T_i$$

$$d_i = |f_i - m_i|$$

where

M_i = expected number of failures for data set: (based on the pooled data sets)

d_i = absolute value of the differences between the expected number of failures and the actual failures for data set i.

Next, lower and upper limits are calculated for the Poisson distribution:

$$U_i = [M_i + d_i] \text{ (if } U_i = f_i \text{, set } U_i = f_i - 1)$$

$$L_i = <M_i - d_i> \text{ (if } L_i = f_i \text{, set } L_i = f_i + 1)$$

$$\text{(if } L_i < 0 \text{, set } L_i = 0)$$

U_i = upper limit for data set i

L_i = lower limit for data set i

[ ] = rounded down to integer value

< > = rounded up to integer value

The probability that f_i failures would occur in data set i given the population failure rate is λ, is expressed by the Poisson distribution:

$$P_i = 1 - \sum_{j=L_i}^{U_i} P_{ij}$$

$$1 - \sum_{j=L_i}^{U_i} e^{-M_i} \frac{M_i^{\,j}}{j!}$$

The individual probabilities, P_i, are the significance probabilities for the individual distributions. It is required to test whether the ensemble of P_i taken together represents an improbable configuration under the null hypothesis which is that the underlying distributions have the same constant failure rate (λ).

The test is done as follows:

$$C_i = -2 \ln P_i$$

$$C = \sum_{i=1}^{n} C_i$$

Find Cr for $\alpha = .05$ (5% level of significance) and 2n degrees of freedom from the tables of chi square.

If C>Cr reject the null hypothesis (that all of the populations have the same failure rate.)

If the null hypothesis is not rejected, the data sets can be pooled and the common failure rate λ used.

If the null hypothesis is rejected, engineering and statistical analysis is required to remove data sets from the pooled data until the null hypothesis is not rejected.

EXAMPLE 1:

DATA SET	T_i	F_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	12.9	6.1	18	7	.0936	4.74
2	144.1	0	3.2	3.2	3	1	.0849	4.93
3	65.6	1	1.4	.4	2	2	1.000	0
4	95.8	1	2.1	1.1	3	2	.5406	1.23
5	128.	3	2.8	.2	3	3	1.000	0
6	281.	15	6.2	8.8	14	0	.0018	12.60
7	78.6	2	1.7	.3	1	1	1.000	0
8	484.8	0	10.7	10.7	21	1	.0016	12.93
	1865.6	41						$\Sigma C_i = 36.43$

pooled - $\lambda = 21.98$ fits

$C = 36.43$

2n degrees of freedom = 16

(from chi-square dist. at $\alpha = .05$) Cr = 26.30

Since C>Cr ---- the null hypothesis, that all of the populations have the same failure rate, is rejected.

EXAMPLE 2:

DATA SET	T_i	f_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	19.5	.5	20	20	1.0	0
2	65.6	1	2.2	1.2	3	2	.536	1.2
3	95.8	1	3.2	2.2	5	2	.277	2.57
4	128.	3	4.2	1.2	5	4	.641	.89
5	281.	15	9.3	5.7	14	4	.070	5.33
6	78.6	2	2.6	.6	3	3	1.02	.0
	1236.4	41						9.99

Pooled λ = 33.16 fits

C = 9.99

2n degrees of freedom = 12

Cr = 21.03

C<Cr - accept null hypothesis --

All data sets have the same failure rate (λ = 33.16 fits).

APPENDIX B

ENVIRONMENTAL DESCRIPTION

Environment	Nominal Environmental Conditions
Ground, Benign	Nearly zero environmental stress with optimum engineering operation and maintenance.
Space, Flight	Earth orbital. Approaches ground, benign conditions without access for maintenance. Vehicle neither under powered flight nor in atmospheric reentry.
Ground, Fixed	Conditions less than ideal to include installation in permanent racks with adequate cooling air, maintenance by military personnel and possible installation in unheated buildings.
Ground, Mobile (and Portable)	Conditions more severe than those for ground, fixed, mostly for vibration and shock. Cooling air supply may also be more limited, and maintenance less uniform.
Naval, Sheltered	Surface ship conditions similar to ground, fixed, subject to occasional high shock and vibration.
Naval, Unsheltered	Nominal surface shipborne conditions but with repetitive high levels of shock and vibration.
Airborne, Inhabited	Typical cockpit conditions without environmental extremes of pressure, temperature, shock and vibration.
Airborne, Uninhabited	Bomb-bay, tail, or wing installations where extreme pressure, temperature, and vibration cycling may be aggravated by contamination from oil, hydraulic fluid, and engine exhaust. Classes I and Ia equipment of MIL-E-5400 should not be used in this environment.
Missile, Launch	Severe conditions of noise, vibration, and other environments related to missile launch, and space vehicle boost into orbit, vehicle re-entry and landing by parachute. Conditions may also apply to installation near main rocket engines during launch operations.