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STORAGE RELIABILITY OF MISSILE MATERIEL PROGRAM

STORAGE RELIABILITY ANALYSIS SUMMARY REPORT

VOLUME I. ELECTRICAL AND ELECTRONIC DEVICES

RAYTHEON COMPANY

PREPARED FOR
ARMY MISSILE COMMAND

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STORAGE RELIABILITY
OF
MISSILE MATERIEL PROGRAM

RAYTHEON

RAYTHEON COMPANY
EQUIPMENT DIVISION

LIFE CYCLE ANALYSIS DEPARTMENT
HUNTSVILLE, ALABAMA

STORAGE RELIABILITY
OF
MISSILE MATERIEL PROGRAM

STORAGE RELIABILITY ANALYSIS
SUMMARY REPORT
VOLUME I
ELECTRICAL & ELECTRONIC DEVICES

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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 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 Command to provide detailed analyses of missile materiel and to generate reliability prediction data. A missile material reliability parts count prediction handbook, LC-76-1, has been developed and provides the current prediction data resulting from this effort.

This report provides a summary of the analyses performed under the storage reliability research program and background information for the predictions in LC-76-1. 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 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 Generic 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:

$$R_{NO}(t_{NO}) = e^{-\lambda_{NO} t_{NO}}$$

$$R_O(t_O) = e^{-\lambda_O t_O}$$

$$R_L(t_L) = e^{-\lambda_L t_L}$$

$$R_F(t_F) = e^{-\lambda_F t_F}$$

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-76-1.

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.

TABLE 1-1. REPORT CONTENTS

Volume I Electrical and Electronic Devices

Section	
2.0	Microelectronic Devices
3.0	Discrete Semiconductor Devices
4.0	Electronic Vacuum Tubes
5.0	Resistors
6.0	Capacitors
7.0	Inductive Devices
8.0	Crystals
9.0	Batteries
10.0	Connectors and Connections
11.0	Printed Wiring Boards

Volume II Electromechanical Devices

Section	
2.0	Gyros
3.0	Accelerometers
4.0	Switches
5.0	Relays
6.0	Transducers
7.0	Hi Speed Motors
8.0	Synchros and Resolvers

Volume III Hydraulic and Pneumatic Devices

Section	
2.0	Valves
3.0	Accumulators
4.0	Actuators
5.0	Pumps
6.0	Cylinders
7.0	Compressors
8.0	Filters
9.0	Gaskets and Seals
10.0	Bearings
11.0	Regulators

Volume IV Ordnance Devices

Section	
2.0	Solid Propellant Motors
3.0	Igniters and Safe and Arm Devices
4.0	Solid Propellant Gas Generators
5.0	Misc. Ordnance Devices

Volume V Optical and Electro Optical Devices

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 these 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

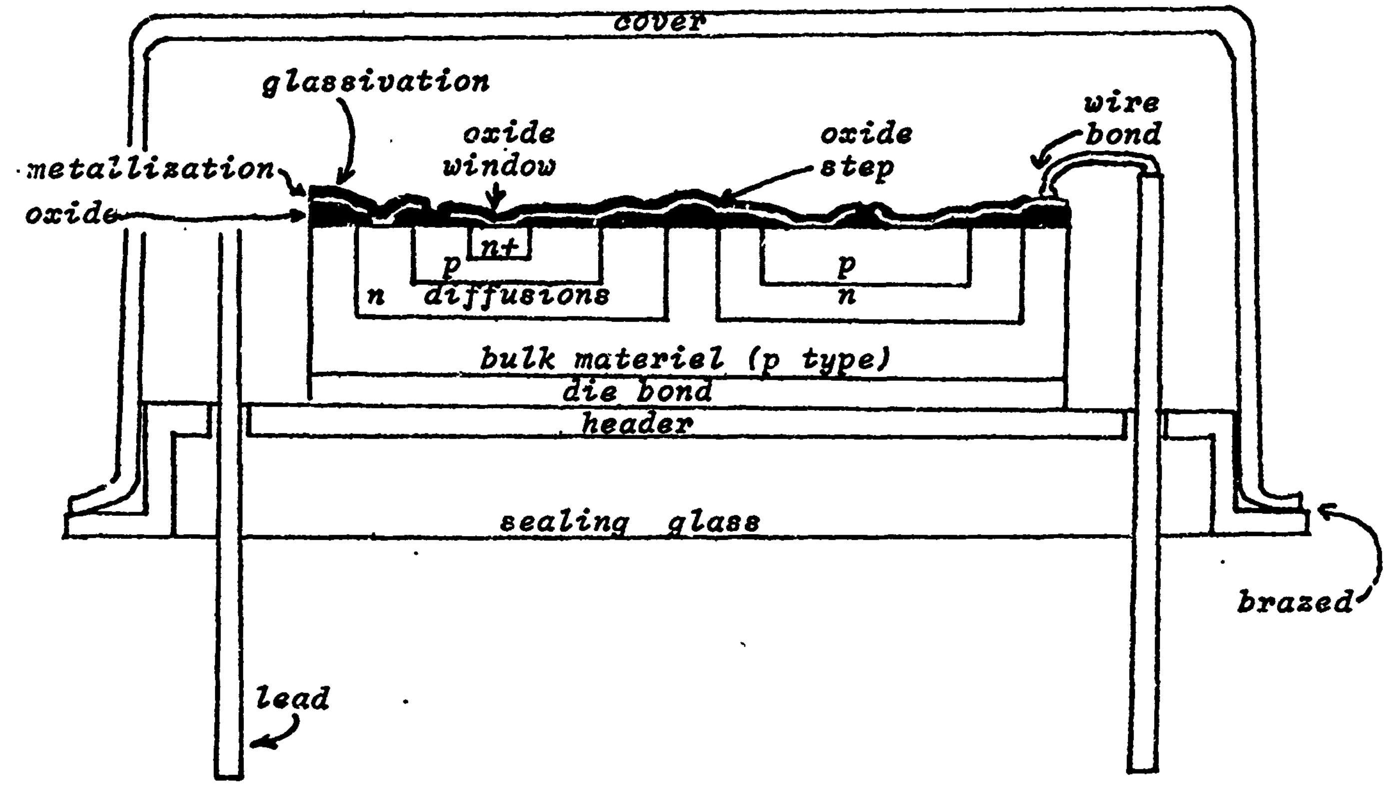

FIGURE 2.1-1. TYPICAL PLANAR MICROELECTRONIC DEVICE CROSS SECTION

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 2.1-2. 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.

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

$$\text{where } x = -6544 \left(\frac{1}{T + 273} - \frac{1}{298} \right)$$

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

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

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

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	0.55
100	8.27
125	20.20
150	65.83
170	132.33

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)

$C_1 = 0.0013$

C_2 (Mechanical Stress Base Failure Rate)

$C_2 = 0.0007$

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

$_L$ = 1 otherwise

Π_Q Quality Factor)

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

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

Π_T (Temperature Factor)

Temperature °C	Π_T
25	0.1
30	0.16
40	0.39
50	0.90
100	30.25
125	95.99
150	442.37
170	1091.57

C_1 (Temperature Base Failure Rate)

$\boxed{C_1 = 0.00054}$

T = Ambient Temperature °C

C_2 (Mechanical Stress Base Failure Rate)

$\boxed{C_2 = 0.0085}$

2.1.3 Non-operational Failure Rate Data

2.1.3.1 Bipolar Digital SSI/MSI Devices

The failure rate models are based on a collection of data which includes over 5 billion hours of storage or non-operating field data with 132 device failures. In addition, over 170 million hours of high temperature storage life data was collected with 616 device failures reported.

Storage data collected is summarized in tables 2.1-3 through 2.1-6. This data is organized in accordance to the metallization and interconnection systems.

Data sources for this analysis were:

a) RADC-TR-73-248 report "Dormancy and Power On-Off Cycling Effects on Electronic Equipment and Part Reliability," August 1973

b) The Reliability Analysis Center Generic Failure Rate Publication - December 1973

c) Sandia Corp. W68 Field Experience

d) Raytheon Improved Hawk Field Experience

e) Planning Research Corporation Data on Standby Devices

f) Special Test Data on the General Electric Site Defense Program.

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. However, 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 2.1-7.

2.1.3.2 Bipolar Linear SSI/MSI Devices

The failure rate models are based on a collection of data which includes over 1.7 billion hours of storage or non-operating field data with 12 device failures reported. In addition over 39 million hours of high temperature storage life data was collected with 87 device failures reported.

Storage data collected is summarized in Tables 2.1-8 and 2.1-9 depending on the metallization and interconnection systems used:

Primary data sources include two missile programs, one special storage program and two reliability data banks.

TABLE 2.1-3. MONOLITHIC BIPOLAR DIGITAL NON-OPERATING DATA (ALUMINUM METALLIZATION, ALUMINUM WIRE)

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS*
Class A	25-30°C	5,861.4	5	.85
	22°C (Nitrogen Atmosp.)	1,071.2	0	(<.9)
	125°C	.113	0	(<8850.)
Class B	25-30°C	3,512.7	11	3.1
	150°C	.155	0	(<6452.)
	250°C	.009	2	222000.
Class C	25-30°C	2,103.0	8	3.8
	125°C	.4	0	(<2500.)
	150°C	64.593	25	387.
	180°C	.11	0	(<9091.)
	200°C	5.954	16	2687.
	250°C	3.1	23	7420.
	300°C	3.656	59	16136.
	350°C	2.152	148	68760.
Class D	25-30°C	4.61	0	(<217.)
	125°C	2.953	5	1693.
	150°C	42.207	39	924.
	175°C	1.643	9	5479.
	180°C	.205	0	(<4878.)
	200°C	6.472	3	463.
	300°C	.788	43	54558.

TABLE 2.1-4. MONOLITHIC BIPOLAR DIGITAL NON-OPERATING DATA (ALUMINUM METALLIZATION, GOLD WIRE)

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURERATE IN FITS*
Class A	250°C	.01	0	(<100000.)
	300°C	.01	0	(<100000.)
	350°C	.01	0	(<100000.)
Class B	25-30°C	2,604.11	77	30.
Class C	150°C	15.848	50	3155.
	175°C	.282	0	(<3546.)
	200°C	.758	9	11873.
	250°C	.315	13	41270.
Class D	25-30°C	.268	0	(<3713.)
	125°C	.307	0	(<3257.)
	150°C	16.875	25	1481.
	180°C	.086	7	81112.
	200°C	.119	40	336417.
	250°C	.063	99	1462000.

* Failures per Billion Hours

TABLE 2.1-5. MONOLITHIC BIPOLAR DIGITAL NON-OPERATING DATA (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. MONOLITHIC BIPOLAR DIGITAL NON-OPERATING DATA (GOLD BEAM SEALED JUNCTION)

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. 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%)

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.

No data was available on gold metal system or beam lead systems.

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. Coefficients of correlation for the linear data points to the digital prediction models were calculated to be 0.899 for quality class C and 0.933 for class D devices with aluminum metallization/aluminum wire systems. Insufficient data points were available on devices with aluminum metallization/gold wire systems to estimate a correlation.

Based on this close 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 for the linear data a decision was made to use the same Arrhenius function developed for the digital data points.

Following the decision to use the digital prediction models, data on storage duration, device function, package type, die attach method and glassivation was analyzed for linear devices and 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.

No data on failure mechanisms was available for the linear devices in storage. Since the bipolar linear device construction is identical to the digital device, no significant difference would be anticipated. The primary operational failure modes for linear devices which are not as predominant for digital devices are drift and inversion phenomenon. The failure modes may be

TABLE 2.1-8. MONOLITHIC BIPOLAR LINEAR NON-OPERATING DATA (ALUMINUM METALLIZATION, ALUMINUM WIRE)

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS*
Class A	150°C	.038	0	(<26316.)
Class B	25-30°C	556.266	2	3.59
	150°C	.076	0	(<13158.)
Class C	150°C	9.709	4	411.
	180°C	7.959	0	(<126.)
	200°C	3.034	1	330.
	250°C	.338	3	8876.
	300°C	.292	3	10274.
	350°C	.069	4	58309.
Class D	100°C	.010	0	(<100000.)
	150°C	13.392	15	1120.
	300°C	.131	9	68702.
	350°C	.041	29	710784.
Class B-A	24°C-Nitrogen Atmosphere	289.966	1	3.45

TABLE 2.1-9. MONOLITHIC BIPOLAR LINEAR NON-OPERATING DATA (ALUMINUM METALLIZATION, GOLD WIRE)

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS*
Class B	25°-30°C	114.	6	53.
Class C	150°C	2.880	6	2083.
Class D	150°C	.896	4	4463.

TABLE 2.1-10. MONOLITHIC BIPOLAR LINEAR NON-OPERATING DATA (METALLIZATION/WIRE TYPE UNKNOWN)

QUALITY LEVEL	AMBIENT TEMPERATURE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS*
Class A	25°-30°C	535.534	1	1.86
Class B	25°-30°C	235.534	2	8.49

caused by ionic contamination or defects in the chip surface and normally require a certain amount of operational time for their occurrence. Therefore, the bipolar linear device failure mechanisms in storage would be similar to those reported for digital devices which include oxide defects, failed wire bonds, diffusion defects, failed die bonds and lead failures.

2.1.3.3 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 2.1-11. 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 2.1-12.

2.1.3.4 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.

2.1.3.5 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.

TABLE 2.1-11

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 2.1-12

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

The storage data collected is summarized in Tables 2.1-13 through 2.1-15. 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 2.1-16.

TABLE 2.1-13. 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 2.1-14. 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 2.1-15. 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 2.1-16

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)

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

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_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_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 2.2-2 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	.020
42	.016	.015	99	.029	.020
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

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

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

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

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_Q (Quality Factor)

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

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	.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	10.0
Missile, Launch	

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-35310 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_Q (Quality Factor)

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

C_1 & C_2 (Complexity Factors)

No. Bits	ROMS C_1	ROMS C_2	RAMS C_1	RAMS 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_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	2[illegible].
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 2.2-7 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR BIPOLAR BEAM LEAD, BIPOLAR ECL and MOS MEMORIES

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

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	.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.		

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_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

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

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

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.

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

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.

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

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 $\leq$ 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 Dice	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_iO_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 799.2 million storage hours with 23 failures reported and 1.5 million hours of accelerated storage life tests with 7 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 28.8 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.

Of the thirty 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

Ambient Temperature	Technology	Storage Hours (millions)	No. of Failures	Failure Rate in Fits
25°C	Thin Film	43.246	1	23.1
25°C	Thick Film	474.914	19	40.0
25°C	Thick Film	146.000	1	6.85
25°C	Thick Film	135.080	2	14.8
70°C	Thick Film	.400	0	(<2500.)
125°C	Thin Film	.098	2	20408.0
150°C	Thin Film	.680	3	4412.
150°C	Thick Film	.261	2	7663.
200°C	Thick Film	.011	0	(<90090.)

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 ($\pm$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 ($\le$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: Forrall 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 120	.0010	.0010	1500	.19	2.8
150	.0016	.0010	2000	.35	10.0
200	.0029	.0010	2500	.56	-
250	.0046	.0010	3000	.82	-
300	.0068	.0022	3500	1.1	-
350	.0093	.0044	4000	1.5	-
400	.012	.0080	4500	1.9	-
450	.016	.014	5000	2.4	-
500	.020	.022	5500	2.9	-
550	.024	.033	6000	3.6	-
600	.029	.048	6500	4.1	-
650	.034	.069	7000	4.8	-
700	.039	.096	7500	5.5	-
750	.045	.13	8000	6.3	-
800	.052	.17	8500	7.1	-
850	.059	.23	9000	8.0	-
900	.067	.29	9500	9.0	-
950	.074	.37	10000	10.0	-
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 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 Figure 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 7 and 9 for Class A, small scale integration (SSI), digital devices at two operation junction temperatures: 35°C and 75°C; for Class B the ratios were 4 and 5; for Class C devices, 23 and 30; and for Class D, 86 and 114.

For medium scale integration (MSI), the ratios for Class A were 15 and 25; Class B, 9 and 14; Class C, 54 and 89; and Class D, 204 and 334.

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 many 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 Class C, 2.2 and 3.0 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, 0.9 and 1.4; Class C, 5.3 and 8.7; and Class D, 1.7 and 2.7.

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.

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	.83	7	15	9	25	17
B	2.91	4	9	5	14	10
C	3.73	23	54	30	89	62
D	9.34	86	204	114	334	233

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	8.5	.6	1.5	.8	2.4	1.7
B	29.8	.4	.9	.5	1.4	1.0
C	38.3	2.2	5.4	3.0	8.7	6.1
D	1150.0	.7	1.7	.9	2.7	1.9

*Failures per Billion Hours.

FIGURE 2.5-1. MONOLITHIC BIPOLAR DIGITAL 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
SSI	5
MSI	14

ALUMINUM METALLIZATION/GOLD WIRE

Complexity Level	Average Operating to Non-Operating Failure Rate Ratio
SSI	0.5
MSI	1.4

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. Therefore, these are preliminary and will be further investigated in subsequent reports.

2.5.2 Bipolar Linear SSI/MSI Devices

A comparison of the failure rates for non-operational and operational environments was made using the non-operating model developed here and the MIL-HDBK-217B operational model. The comparison is presented in Figure 2.5-2. 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 10 and 26 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 15; for Class C devices, 38 and 93; and for Class D, 140 and 347.

For medium scale integration (MSI), the ratios for Class A were 40 and 131; Class B, 23 and 75; Class C, 141 and 468; and Class D, 527 and 1751.

Failure rates for linear 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 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 13.7 and for Class D, 1.1 and 2.8.

For MSI devices, the ratios for Class A were 3.8 and 12.8; Class B, 2.2 and 7.3; Class C, 13.7 and 45.5; and Class D, 4.3 and 14.2.

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 2.5-2.

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	16350.0	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	.83	10	40	26	131	31
B	2.91	6	23	15	75	18
C	3.73	38	144	93	468	112
D	9.34	140	527	347	1751	418

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	8.5	1.0	3.8	2.5	12.8	3.0
B	29.8	.6	2.2	1.4	7.3	1.7
C	38.3	3.6	13.7	9.0	45.5	10.9
D	1150.0	1.1	4.3	2.8	14.2	3.4

*Failures per Billion Hours.

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

TABLE 2.5-2.

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

Complexity Level	Average Operating to Non-Operating Failure Rate Ratio
SSI	15
MSI	75

ALUMINUM METALLIZATION/GOLD WIRE

Complexity Level	Average Operating to Non-Operating Failure Rate Ratio
SSI	1.4
MSI	7.3

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. Therefore, these are preliminary results which should be further investigated.

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 prominent.

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

The information presented for digital and linear devices is a summary of document numbers LC-76-IC1, "Monolithic Bipolar SSI/MSI Digital Integrated Circuit Analysis," dated May 1976 and LC-76-IC2 "Monolithic Bipolar SSI/MSI Linear Integrated Circuit Analysis," dated May 1976. Refer to those documents for details of the data collection and analysis, development of models, definition of failure mechanisms, and technical description of the devices themselves.

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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 0.82 fits (failures per billion hours) for silicon transistors; 0.77 fits for field effect transistors; 1.1 fits for general purpose diodes; and 0.55 fits for Zener and Avalanche Diodes; and 3.3 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)

$$\boxed{0.00082}$$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	0.3
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)

0.00077

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)

$\boxed{0.0011}$

Π_Q (Quality Factor)

Quality Level	Π_Q
JANTX	0.09
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)

0.00055

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)

$$\boxed{.0033}$$

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 over 18 billion hours with 36 failures reported. This includes data from six different programs. The breakdown of storage hours and failures for each source (identified by code names A through F) is shown in Tables 3.1-1 through 3.1-6). In cases where definition of device type and application was not possible, the data was aggregated into an "all types" category. For example, programs E and F utilized JANTX transistors, however further designation was not possible.

The aggregation of storage hours and failures from all five programs is shown in Table 3.1-7. 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 3+. Field effect transistor data indicates for JANTX devices to be in the same general failure rate range as the silicon NPN and PNP devices. No 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 30 billion part hours with 57 failures reported. This includes data from four different programs. The breakdown of storage hours and failures for each program (identified by code names A through D) is shown in Tables 3.1-8 through 3.1-11. In cases where the definition of device type and application was not possible, the data was aggregated into an "all types" category.

The aggregation of storage hours and fialures from all three programs is shown in Table 3.1-12.

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 11+.

The present storage data on Zener Diodes does not show a difference between the JAN and JANTX devices. The JANTX data shows 3 failures in approximately 1.1 billion hours for a storage failure rate of 2.8 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 five times that of the Silicon General Purpose Diodes JANTX quality.

Only JANTX data was available on microwave diodes showing a failure rate of 20 fits.

Insufficient data on Thyristor and Varactor diodes is available for analysis.

TABLE 3.1-1. SOURCE A TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Transistors JAN All Data	70794	1.034	2	1.93
Silicon PNP (All)	3496	.051	0	(<19.59)
Signal	2622	.038	0	(<26.12)
Power		-	-	-
Switching	874	.013	0	(<78.37)
Silicon NPN (All)	29716	.434	2	4.61
Signal	27968	.408	2	4.90
Power	874	.013	0	(<78.37)
Switching		-	-	-

TABLE 3.1-2. SOURCE B TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Transistors JANTX				
All Data	376596	4949.075	5	1.010
Silicon PNP (All)	93198	1224.771	2	1.633
Single	86858	1141.453	2	1.752
Dual	6340	83.318	0	(<12.002)
Silicon NPN (All)	189566	2491.201	2	.803
Single	185762	2441.210	2	.819
Dual	3804	49.991	0	(<20.004)
FET (All)	93198	1224.771	1	.816
Single	81786	1074.799	1	.930
Dual	11412	149.972	0	(<6.668)
Microwave Power	634	8.332	0	(<120.)

TABLE 3.1-3. SOURCE C 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 3.1-4. SOURCE D TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Transistor JANTX All Data	881	27.342	0	(<36.6)
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 3.1-5. SOURCE E TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	STORAGE HOURS X 10^5	NUMBER FAILED	FAILURE RATE IN FITS
Transistors JANTX All Data	3.3	0	(<303.)

TABLE 3.1-6. SOURCE F TRANSISTOR NON-OPERATING DATA

DEVICE TYPE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Transistors JANTX All Data	15.9	1	62.89

TABLE 3.1-7. TRANSISTOR NON-OPERATING DATA - ALL SOURCES

	COMBINED DATA - ALL SOURCES					
	JAN PARTS			JANTX PARTS		
DEVICE TYPE	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Transistors All Data	2562.	18	7.02	15658.	18	1.15
Silicon PNP	51.	0	(<19.6)	2559.	3	1.17
Silicon NPN	434.	2	4.61	6584.	8	1.21
Germanium NPN	-	-	-	21.	0	(<48.0)
Germanium PNP	-	-	-	45.	0	(<22.3)
FET	-	-	-	1299.	1	.77
Unijunction	-	-	-	2.	0	(<500.)
Microwave Power	-	-	-	8.	0	(<125.)

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

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Diodes JAN				
All Data	146832	2144.	5	2.33
Silicon	67298	982.	0	(<1.18)
Switching	24472	357.	0	(<2.80)
Signal	42826	625.	0	(<1.60)
Zener	16606	242.	0	(<4.12)
Regulator	13110	191.	0	(<5.22)
Reference	3496.	51.	0	(<19.6)

TABLE 3.1-9. SOURCE B DIODES NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Diodes JANTX				
All Data	182592	2399.567	3	1.25
Silicon	152794	2007.971	0	(<.498)
Switching	51988	683.210	0	(<1.46)
Signal	100806	1324.761	0	(<.755)
Zener	13314	174.968	1	5.71
Microwave	7608	99.982	2	20.0
Power	8878	116.646	0	(<8.57)

TABLE 3.1-10. SOURCE C DIODES NON-OPERATING DATA

DEVICE TYPE	JAN STORAGE HOURS X 10^6	JAN NUMBER FAILED	JAN FAILURE RATE IN FITS	JANTX STORAGE HOURS X 10^6	JANTX NUMBER FAILED	JANTX FAILURE RATE IN FITS
Diodes All Data	6871.	41	5.97	18761.	7	.37
Silicon	6264.	41	6.54	-	-	-
Switching	-	-	-	-	-	-
Signal	-	-	-	-	-	-
Zener	607.	0	(<1.65)	898.	1	1.11
Regulator	-	-	-	-	-	-
Reference	-	-	-	-	-	-
Tunnel	-	-	-	2.	0	(<523.)
Varactor	-	-	-	2.	0	(<523.)

TABLE 3.1-11. SOURCE D DIODES NON-OPERATING DATA

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Diodes JANTX All Data	842	25.894	1	38.6
Silicon	465	14.403	0	(<69.4)
Zener	377	11.491	1	87.0

TABLE 3.1-12. DIODES NON-OPERATING DATA - ALL SOURCES

	-------- 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
Diodes						
All Data	9015.	46	5.10	21186.	11	.519
Silicon	7246.	41	5.66	2022	0	(<.494)
Zener	849.	0	(<1.18)	1084.	3	2.77
Tunnel	-	-	-	2.	0	(<500.)
Varactor	-	-	-	2.	0	(<500.)
Power	-	-	-	117.	0	(<8.55)
Microwave	-	-	-	100	2	20.0

3.2 Discrete Semiconductor Operational Prediction Models

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

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

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 over-rated 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_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_{S2}
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_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 3.2-2 MIL-HDBX-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	.0094	.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 3.2-3 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)

T (°C)	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

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

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.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	.0	.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 (^{o}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

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

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.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	.0054	.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_C (Construction Factor)

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

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

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

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

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.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	.0046	.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_F (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

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

λ_b (Base Failure Rate)

T (°C)	Stress Ratio									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
0	.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.

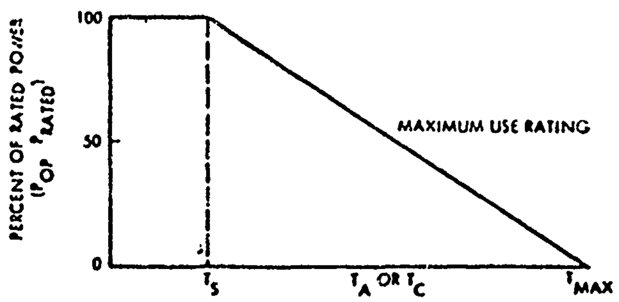


FIGURE 3.2-16 CONVENTIONAL DERATING CURVE

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.

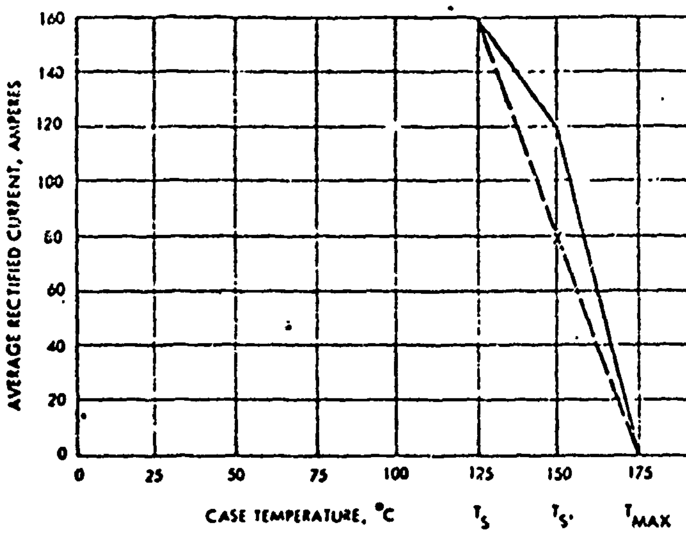


FIGURE 3.2-17 MULTIPOINT DERATING CURVE FOR 1N3263 POWER DIODE

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)

   <u>NOTE</u>: 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

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

<u>and</u> 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

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

<u>and</u> enter λ_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 17 to 94 between operating and non-operating failure rates for JANTX transistors and factors of 24 to 92 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 9 to 50 between operating and non-operating failure rates for JANTX diodes and factors of 10 to 53 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	1.2	20.	17.	8
Silicon NPN	1.2	29.25	24.	8
Germanium NPN	1.2	27.00	23.	8
Germanium PNP	1.2	72.00	60.	8
Field Effect Trans.	.77	72.00	94.	8
JAN				
Silicon PNP	4.1	100.	24.	8
Silicon NPN	4.1	146.	36.	8
Germanium NPN	4.1	135.	33.	8
Germanium PNP	4.1	375.	91.	8
Field Effect Trans.	3.9	360.	92.	8

TABLE 3.3-2. DIODE OPERATING AND NON-OPERATING FACTORS

DEVICE CATEGORY DIODES	NON-OPERATING FAILURE RATE $\times 10^{-9}$	GROUND, FIXED, OPERATING FAILURE RATE $\times 10^{-9}$	G.F.-OPERATING TO NON-OPERATING RATIO	MISSILE LAUNCH TO G.F.-OPERATING RATIO
JANTX				
Silicon	.5	10.5	21	8
Germanium	.5	11.5	23	8
Zener & Avalanche	2.8	25.0	9	8
Microwave	19.8	1000.0	50	20
JAN				
Silicon	5.5	52.5	10	8
Germanium	5.5	57.5	10	8
Zener & Avalanche	2.8	125.0	45	8
Microwave	33.0	1750.0	53	20

4.0 Electronic Vacuum Tubes

This section contains reliability analysis and data on electronic vacuum tubes.

4.1 Storage Reliability Analysis

4.1.1 Failure Modes

A summary of operational failure modes affecting vacuum tubes is shown in Table 4.1-1. Operating hours are not available.

Data storage failure modes is much less extensive. A summary of the failure modes is shown in Table 4.1-2.

4.1.2 Non-Operational Failure Rates

A preliminary estimate of non-operating failure rates is shown in Table 4.1-3 for various tube types. The relatively high failure rate for magnetron tubes is based on data which included some operation.

4.1.3 Non-Operational Reliability Data

Non-operating data was obtained from five sources and is shown in Table 4.1-4. Note that several different environments are represented. The one source (E) which had no periodic check-out on the tubes shows the lowest non-operating failure rates.

Source D data may not be completely applicable to the missile storage environment since the tubes were conditioned after removal from storage. The conditioning included slow heater warm-up; anode, cathode, and helix conditioning by applying high voltage gradually; and RF conditioning by gradually applying RF drive and increasing it to maximum level and pulse width.

TABLE 4.1-1. OPERATIONAL FAILURE MODES FOR DIFFERENT TUBE TYPES

---------- Percent of Failures Under This Mode -----------

	KLYSTRON					
FAILURE MODE	FINAL AMP.	MASTER OSCILLATOR	MIXER OR DRIVER	TETRODE FINAL DRIVER	DIODE SERIES CHANGING	TR RECEIV. PROTECTION
Low Emission	27	23	-	-	-	32
Incorrect Output	16	-	71	-	21	-
Arcing	22	5	-	-	-	11
Open Filament	18	5	14	12	43	32
Shorted	6	-	-	59	15	21
Gassy	-	-	-	29	21	-
Noisy	-	23	-	-	-	-
No Oscillation	-	23	-	-	-	-
Unstable	-	-	15	-	-	-
Misc.	11	21	-	-	-	4

TABLE 4.1-2. NON-OPERATIONAL FAILURE MODES FOR DIFFERENT TUBE TYPES

----------- Percent of Failures Under This Mode ------------

FAILURE MODE	KLYSTRON (1 failure rept.)	TWT (1 failure rept.)	MAGNETRON (4 failures rept.)	RECEIV. & TRANSM.TUBES (13 failures rept.)
Open	100	-	-	15
Short	-	-	-	38
Open heater	-	-	-	15
Incorrect output	-	100	75	31
Arcing	-	-	25	1

TABLE 4.1-3. PRELIMINARY VACUUM TUBE NON-OPERATIONAL FAILURE RATES

TUBE TYPE	$\lambda \times 10^{-6}$
Receiver	.012
Klystron	.078
Magnetron	6.410
TWT	.826
Transmitting	.012

TABLE 4.1-4. VACUUM TUBE NON-OPERATING DATA

SOURCE	TUBE TYPE	NO. OF UNITS	TOTAL PART STORAGE HOURS x 10^6	NO. OF FAILURES	STORAGE FAILURE RATE x 10^{-6}	ENVIRONMENT
A	Sprytron (Hi Rel.)	-	0.410	0	(<2.439)	Unknown
	Tubes (MIL-STD)	-	1.017	14	13.766	
B	TWT	18	0.266	0	(<3.159)	Spacecraft orbit-Standby
C	Magnetron	124	0.624	4*	6.410	Missile Storage (1963 to 65)- Periodic checkout Operating time - 1 to 20 hours Storage time - 2 to 29 months
	TWT	124	0.624	1**	1.663	
D	TWT	25	0.320	0	(<3.121)	Shelf Storage (1970-72) Storage time - 6 to 22 months (conditioned after storage before turn on.)
E	Klystron	874	12.760	1***	0.078	Missile Storage (1967-68) No periodic checkout Storage time - 20 months
	Receiving and Transmitting Tubes (JAN)	72542	1059.113	13****	0.012	

Failure Modes:

* Vibration after field return (12 months); Arcing (15 months); Spectrum too wide (8 months); Moding at start of oscillation (5 months)

** Excessive helix current (5 months)

*** Open (20 months)

**** (3) defective; (5) shorts; (2) opens; (1) low gain; (2) open heaters (20 months)

4.2 Electronic Vacuum Tubes 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_p = device failure rate
λ_b = base failure rate
Π_E = Environmental adjustment factor

The values for these parameters are presented in Figure 4.2-1. The base failure rate is valid providing tubes are replaced before wearout.

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

Figure 4.2-1 MIL-HDBK-217B OPERATIONAL FAILURE RATE MODEL FOR ELECTRONIC VACUUM TUBES

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

λ_b (Base Failure Rate)

Tube Type	λ_b
RECEIVER	
Triode, Tetrode, Pentode	5
Power Rectifier	10
KLYSTRON	
Low Power (e.g. local oscillator)	30
High Power	200
MAGNETRON	
Medium Power (<1Mw. peak)	70
High Power (≥1Mw. peak)	150
TWT	30
TRANSMITTINC	
Triode	75
Tetrode & Pentode	100
CRT	15
THYRATRON	50
λ_b valid providing tubes are replaced before wearout.	

Π_E (Environmental Factor)

Environment	Π_E
Ground, Benign	0.5
Space Flight	0.5
Ground, Fixed	1.0
Airborne, Inhabited	6.5
Naval, Sheltered	6.5
Ground, Mobile	10.0
Airborne, Uninhab.	10.0
Naval, Unsheltered	10.0
Missile, Launch	80.0

4.3 Operational/Non-Operational Failure Rate Comparison

Table 4.3-1 presents a comparison of operational and non-operational failure rates. The operational, ground fixed, failure rates were obtained from the MIL-HDBK-217B model assuming low power or medium power tubes as applicable.

The missile launch to ground, fixed operating ratio was obtained directly from MIL-HDBK-217B.

TABLE 4.3-1. VACUUM TUBE OPERATING AND NON-OPERATING FACTORS

TUBE TYPE	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
Receiver	12	5000	420	80
Klystron	78	30000	380	80
Magnetron	6410	70000	11	80
TWT	826	30000	36	80
Transmitting	12	750000	62500	80

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

Resistor Type	MIL-STD	HI-REL
Carbon Composition	0.11	0.11
Film	0.11	0.033
Wirewound	1.80	0.243
Variable	12.2	8.06
Thermistor	27.8	-

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 61 billion part hours from several programs, with 10 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. It does indicate very little difference between MIL-STD and Hi-Rel carbon composition resistors in storage;

a factor of 3 between MIL-STD and Hi-Rel film resistors; a factor of 7 for wire wound resistors; and a factor of 1.5 for variable resistors.

Data was obtained from four sources and are listed in Tables 5.1-3 through 5.1-6.

TABLE 5.1-2. RESISTOR NON-OPERATING DATA SUMMARY

	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
Composition	9169	1	.109	6897	0	(<.145)
Film	9395	0	(<.106)	30504	1	.033
Wirewound	1109	2	1.803	4116	0	(<.243)
Variable	163	2	12.195	124	1	8.06
Thermistor	108	3	27.778	22	0	(<45.5)

TABLE 5.1-3. SOURCE A RESISTOR NON-OPERATING DATA (MIL-STD)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Composition	309396	4517	1	.221
Film	417772	6099	0	(<.164)
Wirewound	18354	268	0	(<3.731)
Variable	6118	89	1	11.236
Variable, Matched Pair	2622	38	0	(<26.316)
Fixed Variable	1748	26	0	(<38.462)
Thermal	874	13	0	(<76.923)

TABLE 5.1-4. SOURCE B RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Film	1357394	17838	0	(<.056)
Wirewound	45014	592	0	(<1.689)
Potentiometers	4438	58	0	(<17.241)
Thermistor	1268	17	0	(<58.823)

TABLE 5.1-5. SOURCE C RESISTOR NON-OPERATING DATA

DEVICE TYPE	MIL-STD STORAGE HOURS X 10^6	MIL-STD NUMBER FAILED	MIL-STD FAILURE RATE IN FITS	HI-REL STORAGE HOURS X 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 5.1-6. SOURCE D RESISTOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Film	797	25.012	0	(<39.98)
Wirewound	809	25.278	0	(<39.56)
Variable	111	3.488	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:

$$\lambda_b = Ae^{B\left(\frac{T\ +\ 273}{N_T}\right)^{G}}\ e^{\left[\left(\frac{S}{Ns}\right)\left(\frac{T\ +\ 273}{273}\right)^{J}\right]^{H}}$$

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	$9.5(10)^{-4}$	1	298	2	0.5	1	1
RWR	39007	"	"	"	"	"	"	"

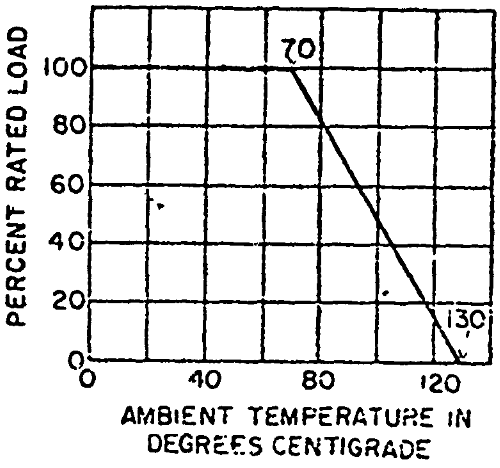
TABLE 5 .2-3

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:

$$V\ \text{applied} = \sqrt{R P\ \text{applied}}$$

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.

TABLE 5.2-1
RESISTOR OPERATIONAL PREDICTION MODELS CROSS REFERENCE

TYPE	MIL-SPEC	STYLE	FIGURE
Fixed, Composition (Insulated)	MIL-R-39008	RCR	5.2-1
	MIL-R-11	RC	5.2-1
Fixed, Film (Insulated)	MIL-R-39017	RLR	5.2-2
	MIL-R-22684	RL	5.2-2
Fixed, Film	MIL-R-55182	RNR	5.2-3
	MIL-R-10509	RN	5.2-3
Fixed, Film (Power Type)	MIL-R-11804	RD/P	5.2-4
Fixed, Wire Wound (Accurate)	MIL-R-39005	RBR	5.2-5
	MIL-R-93	RB	5.2-5
Fixed, Wire Wound (Power Type)	MIL-R-39007	RWR	5.2-6
	MIL-R-26	RW	5.2-6
Fixed, Wire Wound (Power Type) Chassis Mounted	MIL-R-39009	RER	5.2-7
	MIL-R-18546	RE	5.2-7
Thermistor (Bead and Disk Type)	MIL-T-23648	RTH	5.2-8
Variable, Wire Wound (Lead Screw Actuated)	MIL-R-39015	RTR	5.2-9
	MIL-R-27208	RT	5.2-9
Variable, Wire Wound, Precision	MIL-R-12934	RR	5.2-10
Variable, Wire Wound, SemiPrecision	MIL-R-19	RA	5.2-11
	MIL-R-39002	RK	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)

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

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	.00009	.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)

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

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	.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)

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

λ_b (Base Failure Rate)

T (°C)	Ratio of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
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, WIPEWOUND (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	.0093	.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	18.0
Ground, Mobile	20.0
Naval, Unsheltered	23.0
Airborne, Uninhab.	30.0
Missile, launch	70.0

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	.0059	.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	.0358	.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									

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	1.4	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	1.4	NA

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.

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)

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

λ_b (Base Failure Rate)

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
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_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_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_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	.428	.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
RR0900A12A7J1C3	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)

$$\lambda_p = \lambda_b \left(\Pi_{taps} \times \Pi_R \times \Pi_V \times \Pi_E \times \Pi_Q \right) \times 10^{-6}$$

λ_b (Base Failure Rate)

T (°C)	Percent of Operating to Rated Wattage									
	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.0
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	1.53							
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	.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	.210	.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	5.0

* 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	0.11	0.6	5.	7.5
Film	.033	10.5	318.	7.
Wirewound	.243	29.4	121.	11.7
Variable	8.06	780.0	97.	20.
Thermistor	27.80	310.0	11.	12.

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.

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 RATE

	Failure Rate in Fits	
	MIL-STD	Hi Rel
Paper & Plastic	3.8	3.8
MICA	1.2	.97
Glass	.84	.84
Ceramic	.35	.35
Tantalum		
Solid	-	.25
Non-Solid	2500.	9.3
Aluminum Oxide		7.0
Variable	11.	11.

6.1.3 Non-Operating Failure Rate Data

The failure rate table in Section 6.1.2 is based on storage data consisting of over 23 billion part hours with 24 failures reported. Storage hours and failure data for each type of capacitor is shown in Table 6.1-4. No significant differences can be seen in this data between MIL-STD and Hi-Rel parts with one exception. The MIL-STD wet tantalum capacitors show a significantly higher failure rate than the Hi-Rel parts.

Data was obtained from four sources and are listed in Tables 6.1-5 through 6.1-8.

TABLE 6.1-4. CAPACITOR NON-OPERATING DATA SUMMARY

	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
Paper and Plastic	2103.	8	3.8	336.	2	5.95
MICA	858.	0	(<1.16)	1033.	1	.968
Glass	1192.	0	(<.84)	296.	0	(<3.38)
Ceramic	2916.	0	(<.34)	6557.	3	.458
Electrolytic						
All	800.	2	2.5	7124.	7	.983
General Class	-	-	-	2612	2	.766
Solid Tantulum	-	-	-	3935.	1	.254
Non-Solid Tantalum	.8	2	2500.	430.	4	9.3
Aluminum Oxide	-	-	-	147.	0	(<6.80)
Variable						
All	84.	0	(<11.9)	91.	1	11.0
Glass	84.	0	(<11.9)	50.	0	(<20.0)
Ceramic	-	-	-	.3	0	(<3330.)
Air	-	-	-	41.	1	24.4

TABLE 6.1-5. SOURCE A CAPACITOR NON-OPERATING DATA (MIL-STD)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Paper	120612	1761	6	3.41
Film	874	13	0	(<76.92)
MICA	38456	561	0	(<1.78)
Glass	81282	1187	0	(<.84)
Ceramic	53314	778	0	(<1.28)
Porcelain	95266	1391	0	(<.72)
Titanium	6118	89	0	(<11.23)
Tubular Temp.	874	13	0	(<76.92)
Tantalum	54188	791	0	(<1.26)
Differential, Dual Mode	4370	64	0	(<15.62)

TABLE 6.1-6. SOURCE B CAPACITOR NON-OPERATING DATA (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^6	NUMBER FAILED	FAILURE RATE IN FITS
Paper	19020	249.955	0	(<4.00)
MICA	50720	666.546	0	(<1.50)
Ceramic	261842	3441.046	1	.291
Tantulum, Solid	143918	1891.325	0	(<.529)
Variable, Glass	3170	41.659	0	(<24.0)

TABLE 6.1-7. SOURCE C 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 6.1-8. 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.)

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 <u>A</u> 1 <u>M</u> 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:

$$\lambda_b = A \left[\left(\frac{S}{N_S} \right)^H + 1 \right] e^{B \left(\frac{T + 273}{N_T} \right)^G}$$

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,3,-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	CSR	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	.0005	.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.

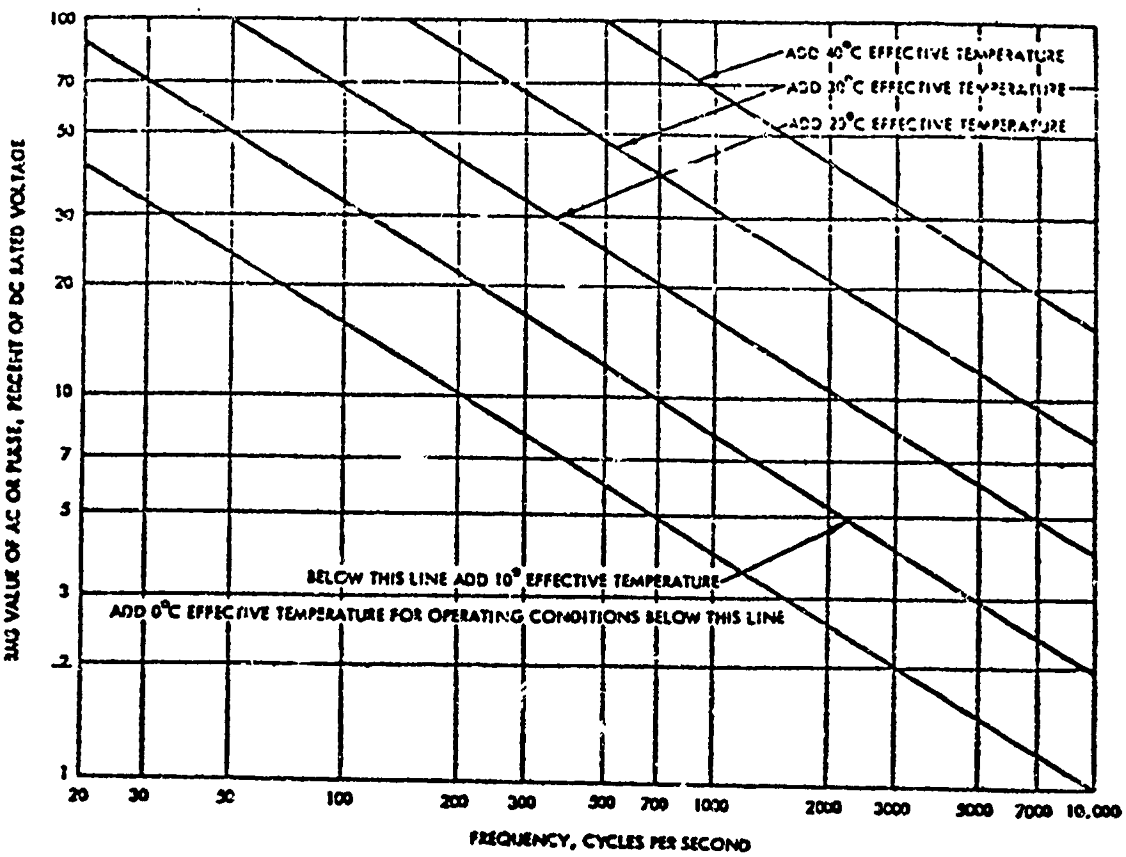


FIGURE 6.2-1a. EQUIVALENT TEMPERATURE INCREASE FOR EFFECTS OF AC OR PULSES FOR PAPER & PLASTIC FILM CAPACITORS (Applicable to MIL-C-14157 & MIL-C-19978, Chars. E, K, M & Q; MIL-C-39022 all styles).

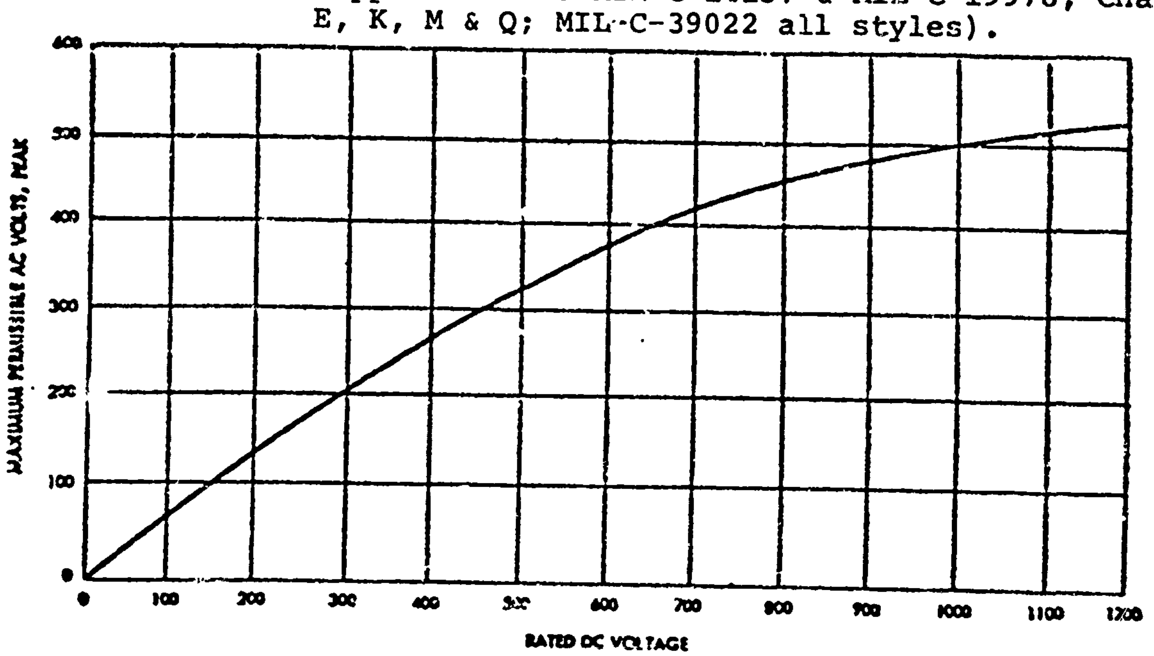


FIGURE 6.2-1b. BASIC RESTRICTION ON USE OF PAPER & PLASTIC FILM CAPACITORS IN AC APPLICATIONS (Applicable only to MIL-C-14157 & MIL-C-19978, Chars. E, K, M & Q; MIL-C-39022 all styles).

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)

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

λ_b (Base Failure Rate)*

T	S, Ratio of Operating to Rated Voltage									
(°C)	.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)

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

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	.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	.0015	.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 (^oC)	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)

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

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	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)

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

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	.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)

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

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	.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	.060
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	.066	.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)

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

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	.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)

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

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	.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)

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

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	.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	.173		
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))

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

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	.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	.015	.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 (^oC)	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
85	.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 and plastic 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	3.0	.4	.1	10
Mica	.97	1.2	1.2	7.5
Glass	0.8	4.0	5	7.5
Ceramic	0.3	20.0	67	7.5
Electrolytic				
Tantalum Solid	.25	20.0	80	10
Tantalum Non-Solid	9.3	28.0	3	15
Aluminum Oxide	7.0	42.0	6	20
Variable	11.0	63.5	6	40

7.0 Inductive Devices

This section contains reliability analyses on inductive devices. Information has been collected and analyzed for the following types of devices: coils, filters and transformers.

7.1 Storage Reliability Analysis

7.1.1 Non-Operational Failure Rate Predictions

The non-operational failure rates for the three types of components analyzed are shown in Table 7.1-1. The available storage data on filters did not report a single failure. The failure rate shown assumes one failure and therefore it is a worst case failure rate. No difference was apparent in the data between MIL-STD and Hi-Rel coils.

TABLE 7.1-1. INDUCTIVE DEVICES NON-OPERATIONAL FAILURE RATES

Device	MIL-STD λ in FITS	HI-REL λ in FITS
Filters & Chokes	9.6	.99
Coils & Inductors	1.3	.94
Transformers	13.9	.99

7.1.2 Non-Operational Failure Rate Data

Information on inductive devices represents data from three sources with a total of over seven billion hours of storage for inductive devices. The breakdown of storage hours and failures for each device is shown in Table 7.1-2. Information as to the specific type of each device and quality levels is broken out by source in Tables 7.1-3, 7.1-4, and 7.1-5.

TABLE 7.1-2. SUMMARY OF INDUCTOR 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
Filters & Chokes	104.	1	9.62	2016.	2	.992
Coils & Inductors	744.	0	(<1.34)	1060.	1	.943
Transformers	649.	9	13.9	3037.	3	.988
Reactors	13.	0	(<76.9)	27.	0	(<37.0)

TABLE 7.1-3. SOURCE A 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	874	12.760	0	(<78.4)
IF	6992	102.083	0	(<9.8)
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	9614	140.364	0	(<7.1)
Toroidal	1748	25.521	0	(<39.2)
Reactors	874	12.760	0	(<78.4)

TABLE 7.1-4. SOURCE B NON-OPERATING DATA FOR INDUCTIVE DEVICES (HI-REL)

DEVICE TYPE	NUMBER DEVICES	STORAGE HOURS X 10^5	NUMBER FAILED	FAILURE RATE IN FITS
Filters				
General Class	145186	1907.989	2	1.05
Coils				
General Class	32968	433.255	1	2.31
Transformers				
General Class	8242	108.314	0	(<9.23)
Reactors	634	8.332	0	(<120.)

TABLE 7.1-5. SOURCE C NON-OPERATING DATA FOR INDUCTIVE DEVICES

	-------- 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
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)

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 spot 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

$$\underbrace{\text{TF}}_{\text{MIL-T-27}}\quad \underbrace{\text{4}}_{\text{Grade}}\quad \underbrace{\text{R}}_{\substack{\text{Insulation}\\ \text{Class}}}\quad \text{Y}\quad \underbrace{\text{01}}_{\text{Family}}\quad \underbrace{\text{GA}}_{\substack{\text{Case}\\ \text{Symbol}}}\quad \text{203}$$

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

$$\underbrace{\text{LT}}_{\substack{\text{MIL-C-}\\ \text{15305}}}\quad \underbrace{\text{4}}_{\substack{\text{Insulation}\\ \text{Class}}}\quad \text{K}\quad \text{001}$$

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

$$\underbrace{\text{TP}}_{\substack{\text{MIL-T-}\\ \text{21038}}}\quad \text{4}\quad \underbrace{\text{Q}}_{\substack{\text{Insulation}\\ \text{Class}}}\quad \text{X 1100BC001}$$

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	$6.37x10^{-4}$	$7.20x10^{-4}$	$6.06x10^{-4}$	$1.83x10^{-3}$	$2.03x10^{-3}$	$2.6x10^{-3}$
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	$6.37x10^{-4}$	$7.20x10^{-4}$	$6.06x10^{-4}$	$1.83x10^{-3}$	$2.03x10^{-3}$	$2.6x10^{-3}$
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

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

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 7.2-6 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 under operating conditions. Measure power loss or input at normal use frequency.

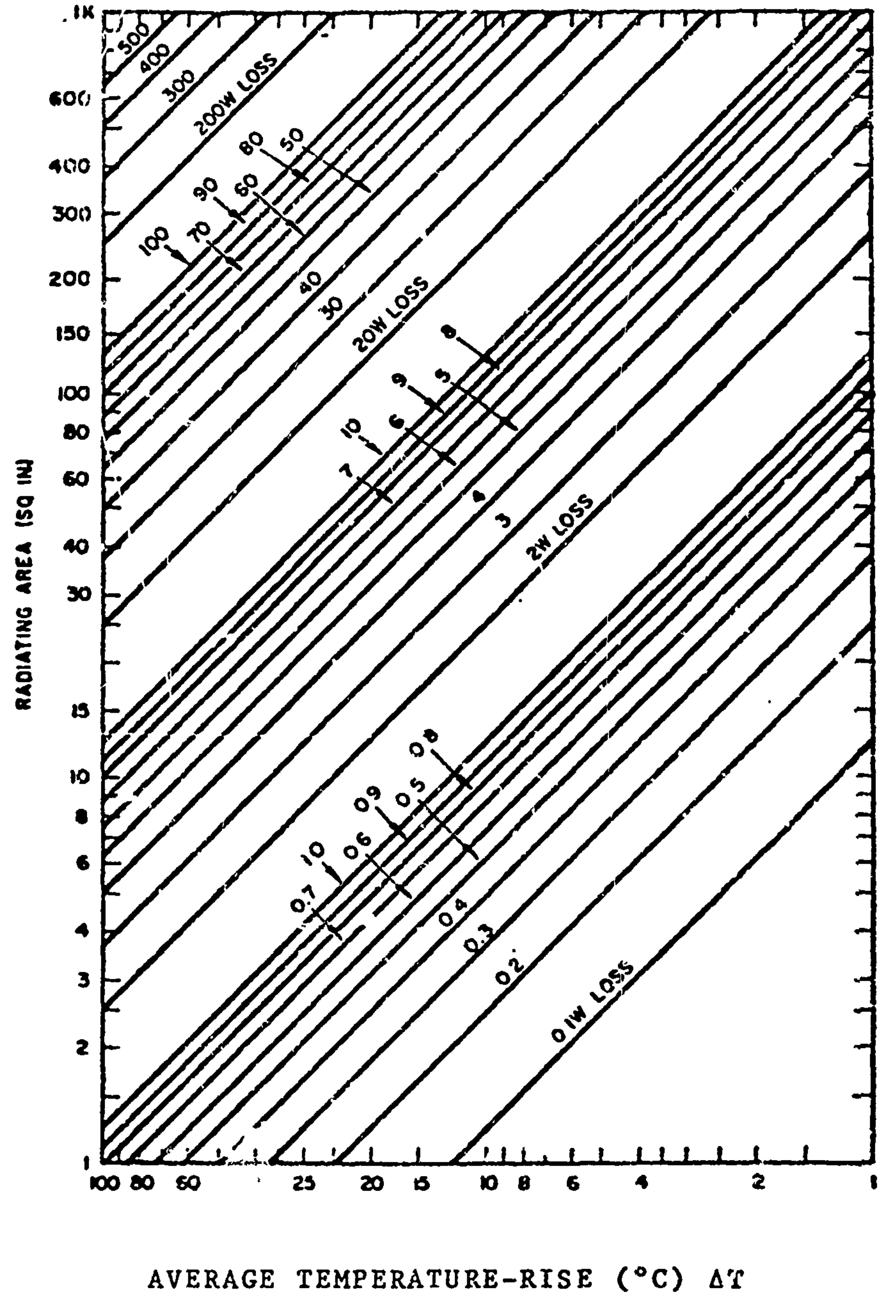
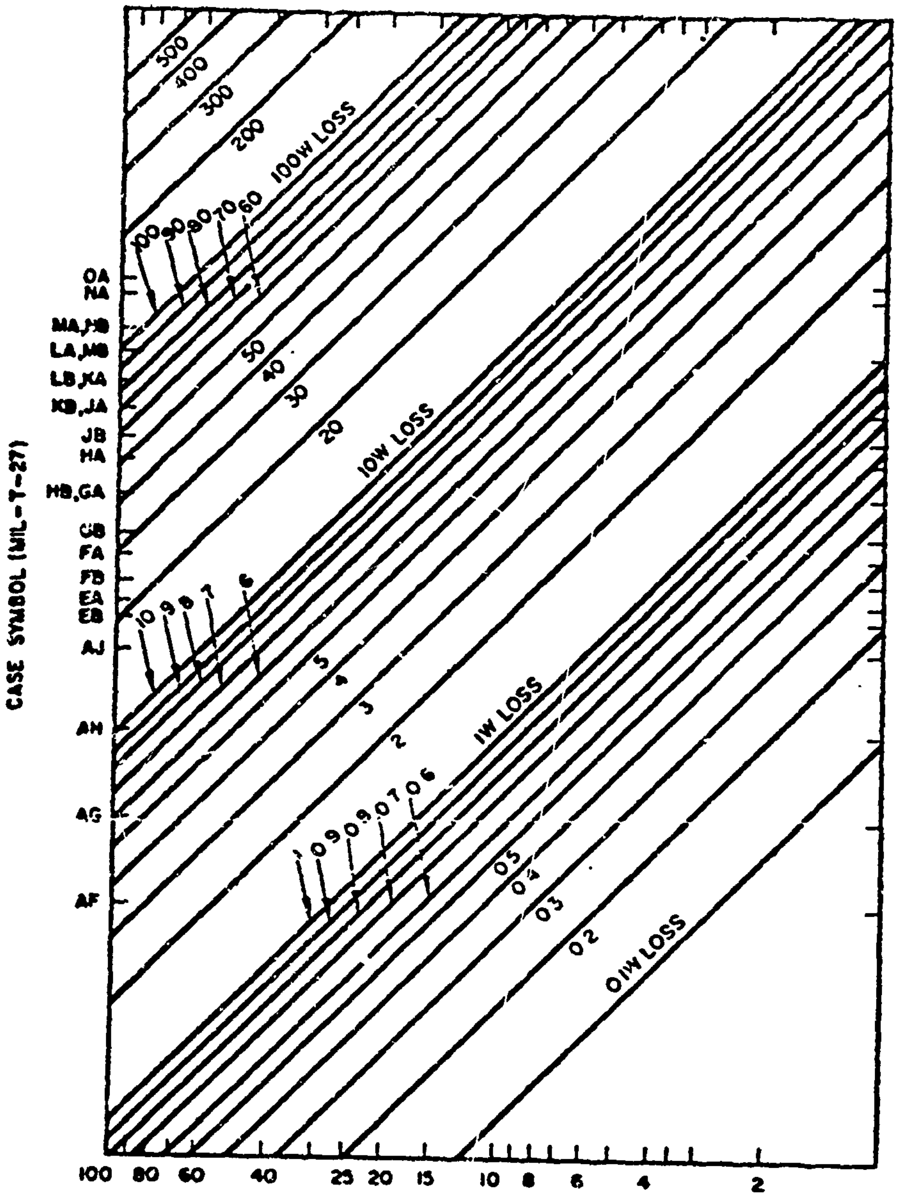


FIGURE 7.2-3. POWER LOSS AND RADIATING AREA KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Step 1A)



AVERAGE TEMPERATURE-RISE (°C), ΔT

FIGURE 7.2-4. POWER LOSS AND CASE SYMBOL KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Step 1B)

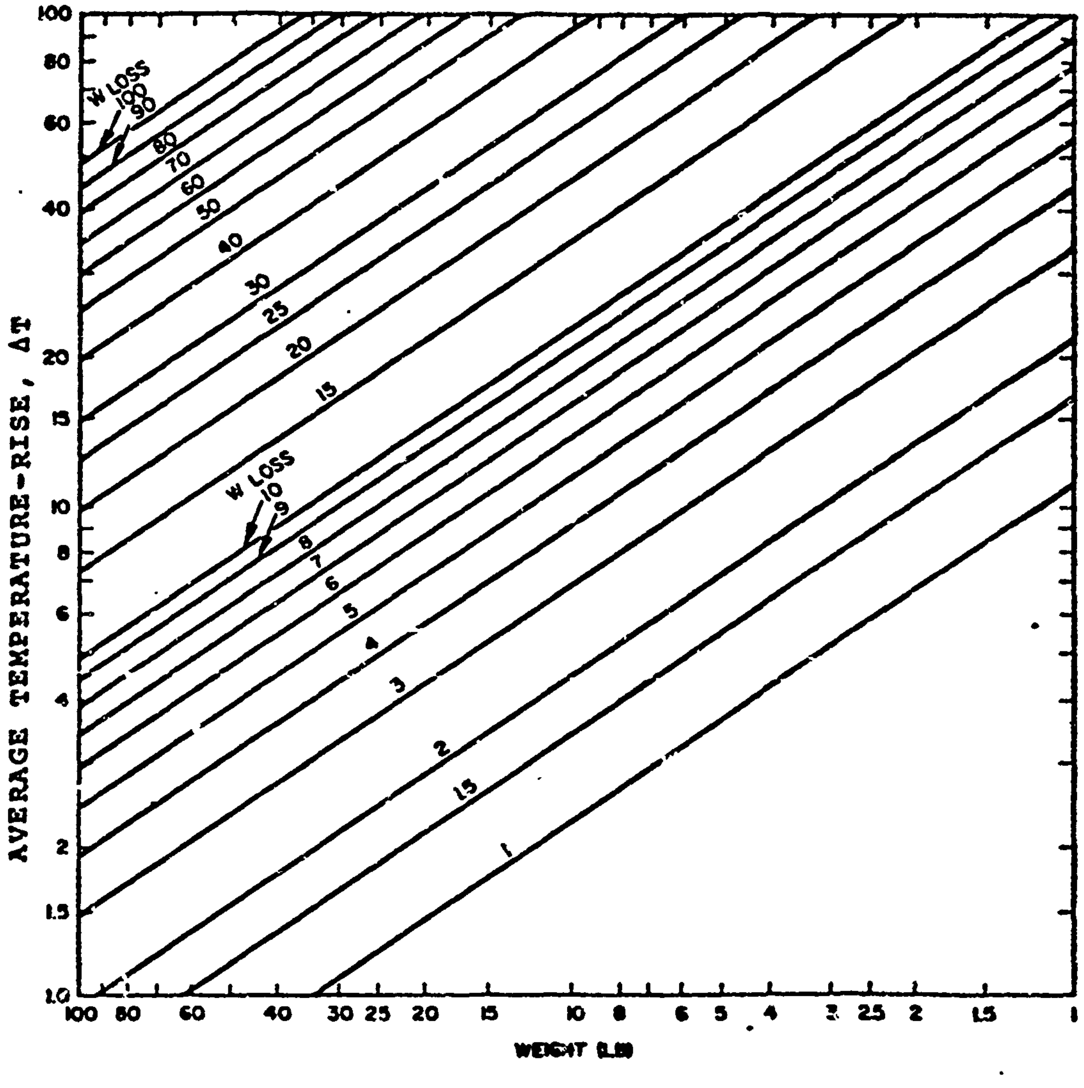


FIGURE 7.2-5. POWER LOSS AND WEIGHT KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Step 1C)

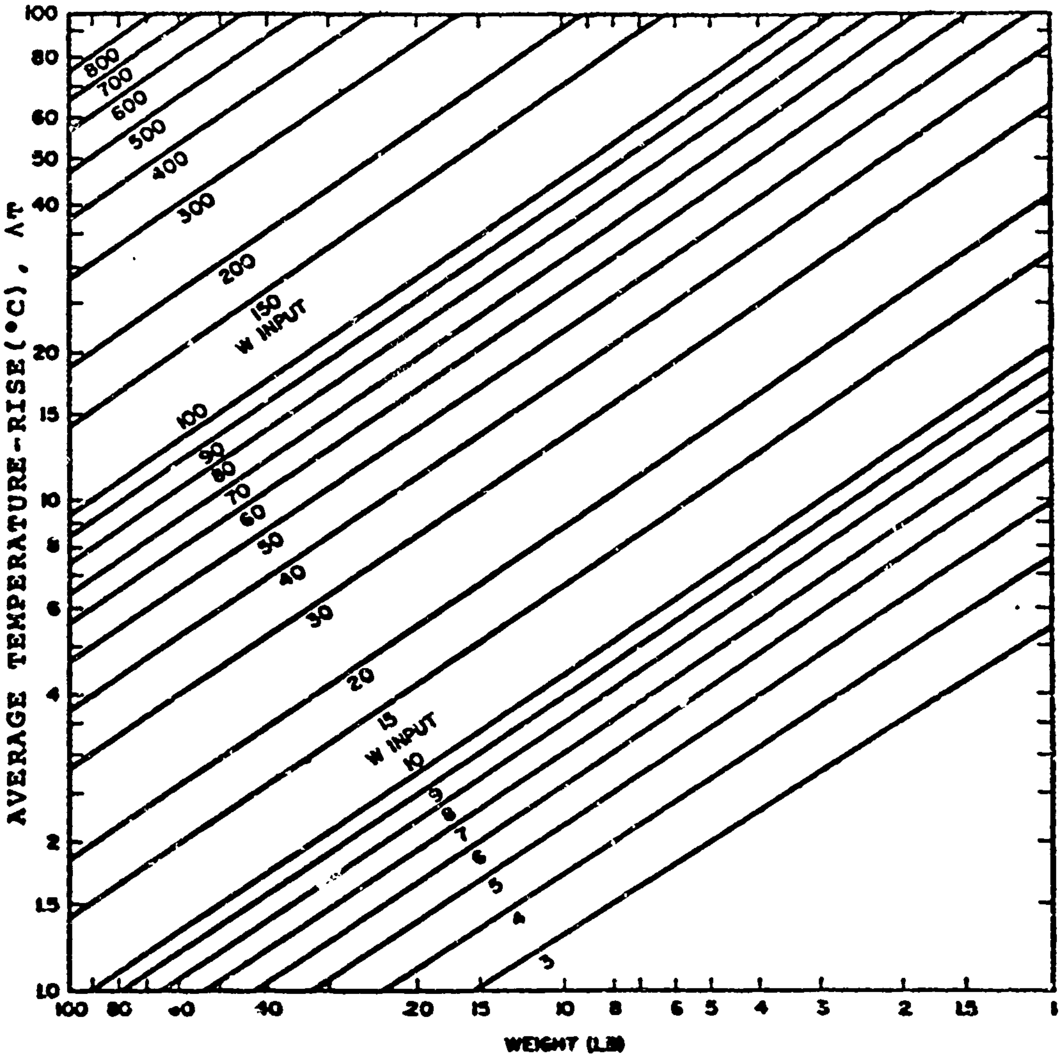


FIGURE 7.2-6. POWER INPUT AND WEIGHT KNOWN: ESTIMATE AVERAGE TEMPERATURE-RISE (Based on 80 PERCENT EFFICIENCY) (Step 1D)

7.3 Operational/Non-Operational Failure Rate Comparisons

Table 7.3-1 summarizes the operational to non-operational failure rate ratios. 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.

The missile launch to ground, fixed operating ratio was obtained directly from MIL-HDBK-217B

TABLE 7.3-1. INDUCTIVE DEVICES 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
Hi-Rel				
Filters	.99	9.6	10	5
Coils	.94	6.4	7	5
Transformers	.99	9.6	10	5
Mil-Std				
Filters	9.6	12.8	1.3	5
Coils	1.3	19.2	1.5	5
Transformers	13.9	19.2	1.4	5

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 44 failures per billion hours.

8.1.2 Non-Operational Failure Data

Forty five million storage hours of crystals with two failures were reported.

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 Batteries

This section contains reliability information on batteries. Missile batteries are usually one shot devices. However, being chemically activated devices, batteries are susceptible to degradation after long periods of storage. The available information did not permit evaluation of aging characteristics.

9.1 Storage Reliability Analysis

9.1.1 Failure Modes and Mechanisms

The principal failure modes and mechanisms and corrective measures for nickel-cadmium batteries are summarized in Table 9.1-1.

9.1.2 Guidelines for Long Life Assurance

9.1.2.1 Design Guidelines

a) Design excess capacity into the battery to reduce the percent depth of discharge and compensate for capacity decrease with usage. The penalty is cost and watt-hours/pound;

b) The negative to positive plate area should be at least 1.5:1 so that the negative plate area can absorb the oxygen generated during recharging, preventing battery overpressure;

c) Use non-woven polyproplene separators since they degrade slower than nylon at higher temperatures. The non-woven configuration wets more readily;

d) Hermetically seal the battery to avoid degradation of other parts by the electrolyte;

e) Either plate the terminal seal braze with nickel or consider using a nickel-titanium braze material to reduce the probability of electrolyte attacking materials containing copper;

f) Use 304 or 304L stainless steel for case and cover material. These materials have proven satisfactory;

g) Use ceramic to metal terminal seals that are more KOH resistant than glass.

9.1.2.2 Process Control Guidelines

a) Employ clean areas during processing and manufacturing to reduce the amount of harmful contaminants. Also, use clean lintfree cotton gloves when handling components. Store components in clean plastic bags when not being processed;

b) Employ clean processes, remove the carbonates and keep the nitrates content down to prevent gas pockets that pop off active material;

c) Flush plates after KOH is used in the process to form active hydroxides to remove carbonates;

d) Flush and brush plates prior to installation to remove contaminants;

e) Coin plates flat. Flex and clean plates prior to assembly. Have resident inspector examine plates for conformity just prior to cell assembly. These actions will reduce the probability of short by either projection of jagged wire filament through the separator or loose particles of plate material or sometimes tab failures;

f) Weigh each plate to be certain weights are within ±3 1/2% of mean. Also, perform actual capacitance measurements to check plate matching. Mismatched cells can prevent full battery charge.

g) Control the brazing temperature-time relationship to prevent excess dwell during brazing operations that can cause active material penetration of ceramic seals;

h) Avoid rapid cooling after brazing to prevent cracked ceramics and brazing voids.

i) Purge cells of air prior to injecting electrolyte to prevent KOH reacting with CO_2 to form carbonates;

j) Place plates under serialized control and provide traceability for separators and electrolyte material to improve the quality of individual cells which has varied more than desired;

k) Require process and test controls for each active element -- plates, separators and electrolyte to reduce end product variability.

9.1.2.3 Test Guidelines

a) Helium leak check the assembled cells. Option-chemical leak check with phenolphthalein;

b) Subject battery during acceptance test to a minimum of three charge/discharge cycles, high impedance short test, and leakage tests. These tests should provide assurance that the basic operating characteristics and construction are satisfactory;

c) X-ray along three axes to find gross battery defects;

d) Conduct a minimum of 30 charge/discharge cycles on assembled cells to eliminate infant mortality and to confirm these tests.

9.1.2.4 Application Guidelines

a) Maintain battery within a -20°C to +22°C temperature range to retard separator deterioration;

b) Store Ni-Cd batteries discharged, shorted and about 0°C to obtain a storage life of about five years.

9.1.3 Non-Operational Failure Rate Data

A total of .2 million storage hours without a single failure were reported. Since no failures occurred and the specifics of the stored batteries were not available it was impossible to assess the aging characteristics.

Based on this information, the failure rate of batteries is less than 5000 failures per billion hours.

TABLE 9.1-1. FAILURE MECHANISM ANALYSIS - NICKEL CADMIUM BATTERIES

Part and Function	Failure Mode	Effect on Battery Output	Rel. Rank	Failure Mechanisms	How to Eliminate/Minimize Failure Mode
A. Plates (Contain charge)	Loss of active material	Lessens capacity available	2	1. Permanent passivation 2. Shedding 3. Redistribution or migration of Cd	1. Operate within 0 to 22°C range. 2. Use proper plate geometry for greater heat dissipation. 3. Don't overcharge excessively. 4. Employ clean processes, remove nitrates and keep carbonate content down to prevent gas pockets from forming underneath that pops off material. 5. Provide excess of cadmium oxide. 6. Start with battery with excess capacity, penalties permitting.
	Short	Lower capacity Lowers voltage High temperatures		1. Plate tabs broken, burned or shortened against case or other plate 2. Plate buckling 3. Projections of jagged wire filaments penetrates separators. 4. Loose particles of plate material or metallic particales introduced during processing. 5 Mechanical environments.	1. Don't weld tabs on - make part of substrate. Use wider tabs. Option: coin plates to receive welded tab. 2. Coin plates including all four edges, smooth. 3. X-ray for misalignment determination. 4. Employ clean processes and materials. Flex and brush off plates just prior to assembly.
	Plate mismatches	Capacity decreased		1. Active material applied uneven or wt. out of tolerance.	1. Require wt. of plates to be within ±3% of that required.
	Memory	Capacity available limited.		1. Temporary passivation. 2. Depressed operating voltage	1. Completely discharge, short, and recharge to wipe out most of memory.
	Contaminates	Lower voltage & current		Carbonate contaminates in plates.	1. Brush and flush plates prior to sealing cells.
B. Separators (separate, insulate, absorb, and conducts)	Low resistance	Capacity decrease	1	Separator deterioration including dissolved, burned, pinpoint penetration, and impregnated with negative plate material.	1. Limit operating temp. range of battery to 0 to 22°C; 0°C preferred. 2. Use alkali resistant material such as polyproplene or nylon. 3. Strict material and process controls. 4. Perform insulation resistance tests on material.
	Contaminates	Lower voltage & current		Material deteriorates, carbonates formed.	1. Use polyproplene for long-life applications. 2. Low battery temps (0°C) retards deterioration.

* Extracted directly from Reference 1.

TABLE 9.1-1. FAILURE MECHANISM ANALYSIS-NICKEL CADMIUM BATTERIES (cont'd)

Part and Function	Failure Mode	Effect on Battery Output	Rel. Rank	Failure Mechanisms	How to Eliminate/Minimize Failure Mode
	Poor KOH absorption and distribution	Higher temperatures. Lower capacity over charging. High voltage on charge and low voltage on discharge	1.	Improper material and weave configuration.	1. Don't use woven nylon. 2. No non-woven configurations except for nylon material. (Polyproplene more difficult to wet than nylon.)
C. Case (Contain and support)	Leak/ burst	Lower capacity, eventually becoming an open circuit.	3	1. Oxygen overpressure due to overcharging. 2. Seal or weld leakage or failure. 3. KOH-case material not compatible. 4. Under designed structure	1. Employ high pressure relief valve/ burst disc for manned mission. 2. Limit overcharge, especially above 80% full charge (third electrode, coulometer, voltage limit, thermistor, stabistor or 2-step regulator). 3. Proper ratio of negative to positive plate capacity. 4. Proper quantity of electrolyte-just enough to wet plates and separator. 5. Leak test assembled cell. 6. Proper process control. Weld per MIL-W-8611A. Passivate per MIL-F-14072, finish 300. 7. Use 304L, cond. A per QQS - 766 or equiv. 8. Ceramic-to-metal seal preferred. Suggest stress relieving design such as a "floating" seal. Consider redundant sealing surfaces.
	Post to cell cover short	Loss of capacity, heating		1. Ceramic failure 2. Electro-metallic bridging across ceramic	1. Minimize quantity of braze used with attention given to its elimination on interior side.
D. Electrolyte	Freeze	No output.	5	1. Low temperatures.	1. Keep storage temp. above - 48°C.
	Contaminate			2. Carbonate & nitrate contaminates	2. Limit carbonate and nitrate concentrations to 0.01 gm/liter and 1 mg/liter or less respectively. 3. Don't expose to air as KOH has infinity for CO_2.
E. Internal Electrical connections (Conduct current)	Open	Partial or complete loss of capacity, voltage.	4	1. Mechanical breakage of cell terminals, plate lugs or welded joints.	1. Strict QC. 2. Avoid overly severe dynamic stresses during usage.

9.2 Operational Failure Rate Data

Operational data collected consisted of three different battery types as shown in Table 9.2-1.

TABLE 9.2-1. BATTERY OPERATIONAL FAILURE DATA

BATTERY	NO. OF FAIL.	OPERATING HRS.	$\lambda \times 10^{-6}$
A	2	60	33333
B	6	1580	5084
C	9	29750	302

The wide discrepancies in failure rates suggest different battery types and applications. Unfortunately the detailed information to verify this is not available. By pooling all the information in Table 9.2-1, the average failure rate is 542 failures per million hours.

Reference:

MCR-72-169, Volume 3, Long Life Assurance Study for Manned Spacecraft Long Life Hardware, K. W. Burrows, Martin Marietta Corp., dated September 1972.

10.0 Connections and Connectors

10.1 Storage Reliability Analysis

The available data on storage failure rate of electrical connections and connectors is shown in Table 10.1-1.

The average failure rate for the data in Table 10.1-1 is 0.13 fit, but all of the failures occur in one classification. Statistical analysis shows that the classification containing the failures is wildly discordant: the expected number of failures for 11603 hours is 1.486 and the probability of seeing even as many as 10 failures in this number of hours is less than 0.00001. Unfortunately, this classification is not further identified, and except for the submarine data, it is not clear to what it could be compared.

The line of data containing the 17 failures gives a worst case failure rate of 1.46 fit. Pooling the remaining data gives a gest case failure rate of .0080 (one failure assumed).

Combining the three sets of data referring to pins gives a total of 80,071.4 million hours with no failures, which gives 90% confidence that the true failure rate lies below 0.028 fit.

Combining the three sets of data referring to soldered connections gives a total of 35,385 million hours with no failures, which gives 90% confidence that the true failure rate lies below 0.065 fit.

TABLE 10.1-1. STORAGE FAILURE DATA FOR ELECTRICAL CONNECTIONS

Failure rate (fit	Source	Failures	Hours (million)	Comment
-	A	0	169.	Soldered
-	A	0	24.5	Stud and nut
-	A	0	163.	20 pin, gold plated
-	B	0	316.	Soldered
-	B	0	5580.	Welded
-	B	0	47.4	Pins
1.5	C	17	11603.	General
-	C	0	6.3	Submarine, general
-	C	0	79861.	Pins
-	C	0	34900.	Soldered
		17	136.115	

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:

$$\lambda_b = A\ e^x$$

$$\text{where} \quad x = \left(\frac{T + 273}{N_T}\right)^G + \left(\frac{T + 273}{T_G}\right)^P$$

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

CONTACT SIZE

AMPERES PER CONTACT	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. Comparable rates from LC-76-EM5 are shown in Figure 10.2-3. The rates shown are the best statistically significant.

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

FIGURE 10.2-3. BEST CONNECTIONS FAILURE RATES FROM LC-76-EM5

Connections	λ_p (10^{-6}/hr.)
Solder	0.00134
Weld	0.00171
Wrap	0.0000103
Crimp	0.0162

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 90% confidence level for pin connectors in Section 10.1 was .028 fit. The operational to non-operational failure rate ratio is 3.2.

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 .83 failures per billion hours.

11.1.3 Non-operational Data

Non-operational data collected consisted of 1210 million hours with one failure reported. Storage conditions are unknown.

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 120.

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

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.

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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 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,

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