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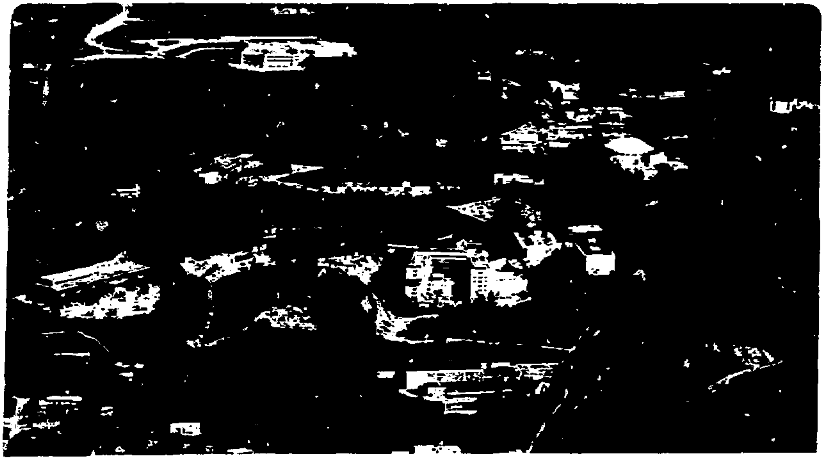
MASTER

February 1980



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Reliability Considerations of Electronics Components for the Deep Underwater Muon and Neutrino Detection System

Branko Leskovar

Abstract

The reliability of some electronics components for the Deep Muon and Neutrino Detection (DUMAND) System is discussed. An introductory overview of engineering concepts and technique for reliability assessment is given. Component reliability is discussed in the contest of major factors causing failures, particularly with respect to physical and chemical causes, process technology and testing and screening procedures. Failure rates are presented for discrete devices and for integrated circuits as well as for basic electronics components. Furthermore, the military reliability specifications and standards for semiconductor devices are reviewed.

Introduction

The Deep Underwater Muon and Neutrino Detection (DUMAND) Project involves creating a large target-detector system, consisting of a three-dimensional array of a minimum of 22,698 optical sensor modules. Čerenkov light resulting from particle cascades will be detected by approximately 22 X 10^3 or 44 X 10^3 photomultipliers which will be housed in optical sensor modules together with an appropriate fluorescent wavelength shifters and signal processing electronics. The modules will be deployed on vertical strings which will be connected to one another by horizontal lines on the ocean floor. Earlier DUMAND Workshops[1,2] described the optical array system and its characteristics with respect to the array configuration and efficiency for observation of both hadronic cascades and muon tracks which result from arriving neutrinos. Also, the array signal processing and data handling system were considered[3,4]. Internal and external noise sources were analyzed. Array signal processing considerations were made, particularly with respect to the detection characteristics of the optical array, array architecture and modes of the array operation. The data handling system considerations were made with respect to trigger requirements, system organization and strategies for minimizing cost.

These efforts and new considerations presented at the DUMAND Signal Workshop, DUMAND Hawaii Center, University of Hawaii, February 11-16, 1980, clearly showed that the reliability of the components of the DUMAND system will be of the utmost importance because of the duration of the experiment and the unusually large number of these electronics subsystems and electrical components. The system must provide an acceptable reliability over a time period of 10 years without service access. The acceptable reliability for the DUMAND System primarily assumes that the system array component failures will occur and accumulate so that the array gradually deteriorates during its 10 year lifetime. The end of life of the array has been defined as a failure (or loss of adequate sensitivity) of 30% of the 22,698 optical sensor modules and associated signal processing and data handling channels. The optical sensor modules, the station logic systems, the strings, the central and the end stations, as defined in Refs. 3 and 4, will use adjustable discriminators, fast analog-to-digital converters, various kinds of memories, microprocessors, real time clocks, high and low voltage power supplies, fast electronics, and power and communication cables. Presently, the DUMAND System signal processing and data handling architecture has not been defined in sufficient detail to enable one to estimate the required system redundancy given the component reliability to ensure the desired life. However, it is possible to estimate and comment on the electronics and electrical components reliability and their life. In an accompanying paper, an attempt has been made to estimate the optical sensor photomultiplier reliability and its life[5]. Based on considerations presented at the DUMAND Signal Processing Workshop, the basic reliability considerations and failure rates for some of these components have been examined and discussed.

Reliability Definitions

The reliability of a device is defined as the probability that it will perform its assigned function(s) for a specified period of time under given conditions. Electronic devices exhibit a characteristic failure pattern as a function of time, as shown in Fig. 1. The failure rate is high but declining during the initial phase. Early failures are due to the design and manufacturing deficiencies and undetected material defects. The end of this period is designated t_1 in Fig. 1.

The second phase exhibits a relatively constant failure rate, independent of time. This failure rate is caused by application stresses. Near the end of the life of the device, failure rates increase due to aging and/or deterioration. This is indicated as t_2 in Fig. 1. Deterioration, for example, in package hermeticity because of the corrosion yields an increased failure rate. The flat portion of the curve is normal operating region. For reliability estimates, the

the failures in this region can be considered random and independent and they are adequately represented by a Poisson process. Such a process, with a failure rate λ, exhibits an exponential failure law:

$$R(t) = \exp(-\lambda t) \tag{1}$$

where R is the reliability or probability that the component will operate successfully for a length of time t. Failure rate λ, usually expressed in number of component failures per 10^6 hours for high reliability components, is a constant for any given set of stress, temperature and quality level conditions. The establishment of points t_1 and t_2 is necessary to determine the useful lifetime for a particular device.

The reciprocal of the failure rate is defined as the mean-time-between-failures, MTBF = $1/\lambda$. The MTBF is a figure of merit by which a component can be compared to another. It is a measure of the failure rate during the useful life period. From the reliability of the individual electronic components, one can determine the reliability of the overall electronic system. The simplest situation occurs if failure of one component is independent of failure of the others and if for successful operation every component must operate. For a system consisting of a series of components, the overall reliability can be obtained by multiplying the reliabilities of the components:

$$R_{system}(t) = \exp(-\lambda_1 t) x \exp(\lambda_2 t) x \cdots x \exp(-\lambda n t), \tag{2}$$

or

$$R_{system}(t) = \exp\left(-t \sum_{x=1}^{n} \lambda_x\right) \tag{3}$$

where λ_S system is the system failure rate. It is equal to the sum of the individual failure rates of n independent components.

System components can be combined in parallel so that when a componet fails there is another component to perform the same function. With this redundancy the system reliability can be expressed by:

$$R_{system}(t) = 1-[1-R_1(t)] \times [1-R_2(t)] x \cdots x [1-R_n(t)] \tag{4}$$

when $R_n(t)$ is the reliability of the nth component.

To improve the system reliability, various redundancy techniques using parallel and serious configurations of components are applied. In certain cases as the best reliability function for solving reliability problems, the Gaussian probability distribution is used. Furthermore, the Weibull distribution, of which the exponential is a special case, has been used in more refined studies. A further elaboration of techniques is given in Ref. 6-7.

Component Failure Rate Prediction

The main use of prediction models at the component level has been in estimating the operational reliability of electronic component subsystems and systems, based upon component-failure rates. The most direct approach to estimate component-faiure rates involves the use of large scale data collection studies. Generally, prediction models can only yield gross estimates of failure rates. The model currently used for simple component failure rates can be expressed in a general form as follows[11]:

$$\lambda_{\text{component}} = \lambda_b \, \pi_E \, \pi_A \, \pi_Q \cdots \pi_n \tag{6}$$

where $\lambda_{\text{component}}$ is the total component failure rate, λ_b is the base failure rate usually determined from a model relating the influence of electrical and temperature stresses on the part, π_E is the environmental adjustment factor which accounts for the influences of the environment other than temperature (such as vibration, humidity, etc.), π_A is the application adjustment factor, π_Q is the quality adjustment factor which takes into account the degree of manufacturing control, and π_n is the symbol for a number of additional adjustment factors which accounts for cyclic effects and other factors that modify significantly the failure rate. Military Standardization Handbook MIL-HDBK-217B-Reliability Prediction of Electronic Equipment[12] provides detailed descriptions and numerical amounts of various adjustment factors for electronic components. For monolitic bipolar and MOS linear and digital devices, the model given by Eqn. (5) has been modified. The principal change has been to separate temperature-dependent and nontemperature-dependent contributions to failure, in a multilevel additive model as follows:

$$\lambda_{\text{component}} = \pi_L \pi_Q (C_1 \pi_T + C_2 \pi_E) \pi_P \tag{7}$$

where $\lambda_{\text{component}}$ is the device failure rate in F/10^6 hours, π_L is the device learning factor, π_Q is the adjustment factor for quality level, π_T is the temperature acceleration factor which value depends upon the device technology, π_E is the adjustment factor for application environment, coefficient C_1 and C_2 are the circuit complexity failure rates, and π_P is the pin factor. Adjustment factors and coefficients are given in MIL-HDBK-217B Handbook for various microelectronic devices.

Reliability of Semiconductor Devices

There are many physical and chemical factors which can influence failure rate of semicoductor components. At present, temperature appears to be the only universally applicable accelerating factor for device degradation rate. Special cases exist where degradation rate is increased or decreased by the presence of an applied field, e.g. ion migration in solids, molecular and electronic polarization, charge transfer, and field-induced or field-enhanced diffusion processes. Furthermore, electromigration in metal conductors is known to be a function of current density as well as temperature.

Semiconductor device reliability are determined basically by device design, the number of in-line process-control inspections used, the level of rejection and the degree of reliability screening. Design factors influencing reliability are related to the semiconductor wafer, and the assembly and packaging. Semiconductor-wafer-related factors which have an impact on reliability are the temperature of the device during operation, junction passivation procedures and materials, and metallization procedures. Assembly and packaging relating factors which influence reliability are chip mounting, bonding procedures, packaging and sealing materials and methods. The process control factors influencing device reliability are the following; methods of implementing process control such as in-process lot acceptance, monitoring and audit, presentation and interpretation of the process control test results, calibration of the test equipment, and quality control of incoming materials and piece parts. In order to establish the device failure rate, the stress testing is utilized to accelerate device failure and establish failure-rate curves in less time than that required for field failure data collection. A variety of electrical, mechanical, and environmental stresses are available for use in product evaluation. Derating factors have also been established to determine application failure rates based upon accelerated stress results[8,9]. Furthermore, to assess the device capability with respect to reliability, the device failure modes are generally determined. The failure analysis is used to improve device design and processing and to aid in determining effective methods for reliability improvement. Techniques of failure analysis are well established. Employed methods with examples of failure mechanisms are described in detail in Ref. 10.

Discrete Semiconductor Devices Failure Rates

Discrete semiconductor devices are classified functionally and constructionally into thirty-five different types in the MIL-STD-701-List of Standard Semiconductor Devices. This document provides a listing of devices which are considered to be standard or are preferred for use in DOD equipment. Because of a wide proliferation of the devices, proven technology and device standardization, semiconductor failure modes are well established,[13] and within limits, can be effectively controlled during processing. Table 1 includes failure rate information for each semiconductor type. The failure rates shown were taken from Ref.11, reflecting airborne environments.

Integrated Circuits Failure Rates

A monolithic integrated circuit is characterized by a single silicon chip with both active and passive components on it, which is suitably packaged and performs well defined functions. This characterization includes varying degrees of complexity from simple circuits up to large scale integrations. Monolithic integrated circuits cover various forms of current technology, such as Transistor-Transistor Logic, Metal-Oxide-Semiconductor, Complementary Metal-Oxide-Semiconductor, etc.[14] Standard devices are listed in MIL-STD-1562-List of Standard Microcircuits, from which selections can be made. Similar standardizing documents do not currently exist for hybrid microcircuits, because they are essentially custom made devices, the approach to their reliability has been made through visual test and inspection techniques. Table 2 provides failure rate range information for digital and linear integrated circuits. The information included in this table is intended to be used for comparing the reliability aspects of integrated circuits and to aid in the selection of the most appropriate devices for a particular application. It can be seen from the table that for digital integrated circuits, the failure rate range is from 0.032 $F/10^6$ hrs to 0.344 $F/10^6$ hrs, depending upon the circuit type, its power level and complexity. For linear integrated circuits, the failure rate varies from 0.096 $F/10^6$ hrs to 0.208 $F/10^6$ hrs. The failure rates shown were taken from Ref. 11 using values for adjustment factors ranging from the worse case to optimum application conditions.

Table 1. Discrete Semiconductor Device Failure Rates

Semiconductor Type		Failure Rate, F/10^6 hrs
Diodes	Silicon, general purpose	0.68
	Silicon, voltage reference	0.85
	Silicon, microwave detector	12.0
	Silicon, microwave mixer	16.0
	Varactor	8.1
	Germanium, microwave detector	35.0
	Germanium, microwave mixer	61.0
Transistors	Silicon, NPN, low power and switching	0.98
	Silicon, NPN, high power > 5 W	0.98
	Silicon, NPN, low power chopper	0.98
	Silicon, PNP, low power and switching	1.6
	Silicon, PNP, high power > 5 W	1.6
	Silicon, PNP, low power chopper	1.6
	Silicon, complementary, NPN/PNP	2.58
	Silicon, field effect N channel and P channel	2.7

Resistor and Capacitor Failure Rates

Resistors have been well documented in MIL-STD-199-Resistors, Selection and Use of. There is a wide variety of available standard types and styles. Failure rate range for resistors, taken from Ref. 11 is given in Table 3 for purposes of comparison. The data again reflect an airborne environment and an M quality level. It can be seen from the table that there is a wide range of

Table 2. Failure Rate Range of Integrated Circuits

Integrated Circuit Type	Failure Rate Range F/10^6 hrs
Transistor-Transistor Logic	0.032-0.180
Complementary Metal-Oxide-Semiconductor	0.044-0.344
Emitter-Coupled Logic	0.056-0.088
Programmable Read Only Memory	0.280
Linear Integrated Circuit	0.096-0.208

failure rates for wire-wound power type and composition type resistors. In these categories, the low failure rates occur for fixed value power types with established reliability while high failure rates are for variable value power type resistors. Generally, extremely high-tolerance fixed-resistors and certain precision type variable resistors, which require a particular output voltage curve, taps or configuration, may possess a questionable reliability.

Similar to resistors, capacitors have been investigated in detail for operational characteristics, applicable ratings, testing, qualification approval, quality control and standardization. Like transistors, they are produced in large quantities which tend to keep unit price low and promotes standardization. Capacitors have been documented in MIL-STD-198-Capacitors, Selection and Use of. Typical failure rate ranges are given in Table 3. There is a wide range of failure rates of mica, ceramic dielectric, and electrolytic capacitors. Low amounts of failure rates occur for particular styles with field established reliability. The failure rates shown in the table are generic failure rates taken from Ref. 12.

Other electronic or electrical components are widely covered by appropriate documents. Transformers and inductors are classified in MIL-STD-1286-Transformers, Inductors and Coils, Selection and Use of. Relays are listed in MIL-STD-1346-Relay, Selection and Use of. A list of failure rates for generic type of the above mentioned components is given in Ref. 12.

Table 3. Failure Rate Range of Resistors and Capacitors

Type of Component		Failure Rate Range, F/10^6 hrs
Resistors	Film, high stability	0.020 - 0.023
	Film, power type	1.3
	Wire-wound-accurate	0.15 - 6.4
	Wire-wound-power type	0.066 - 6.0*
	Wire-wound, precision	5.8
	Wire-wound, lead-screw activated	0.14 - 0.70
	Composition	0.0048 - 20*
Capacitors	Mica dielectric	0.006 - 0.93
	Glass dielectric	0.021
	Ceramic dielectric	0.044 - 2.4
	Tantalum	0.052
	Air dielectric	1.0
	Plastic dielectric	0.0012
	Electrolytic	0.11 - 1.6
	Metallized dielectric	0.0012

*Variable Resistors

Conclusions

Although the DUMAND System signal processing and data handling architecture has not been presently defined to a degree where a realistic assessment of the system reliability and lifetime can be made, it is possible to estimate and comment in general on the reliability of typical System electronics components. High requirements on the system's long term reliability will require the usage of high-reliability components and the application of highly redundant techniques in designing the various subsystems. Highly reliable components, specified, fabricated, tested and screened according to presently available military standards, can significantly help in the design of a high reliability DUMAND System and to make possible an assessment of its probable life. Because the System must provide an acceptable reliability over a period of ten years without maintenance, the DUMAND electronics components may require the screening requirements which offer the highest reliability level. In order to eliminate the incipient failures due to the manufacturing process, a number of quality and screening tests should be employed. Quality tests, including careful inspection and conventional testing, will reduce the number of defective components from production lines. The screening test will remove inferior devices and reduce the failure rate by over stressing devices being tested. The reliability screening will also compress the component early failure period and reduce the failure rate to acceptable levels as quickly as possible. The test and stress levels should be properly selected for particular types and applications of components to reveal inherent weaknesses (and thus incipient failures) without damaging the integrity of the device. If proper test procedures are applied equally to a group of devices manufactured by the same process, the inferior devices will be eliminated from the group. The remaining devices, which have demonstrated the ability to withstand over stress, will show a minimum failure rate under normal rated operating conditions. This can be considered the expected failure rate when the devices are used in a practical system. Generally, the screening tests are particularly well suited to discrete semiconductor components and integrated circuits because of their material and process dependency. For DUMAND System application, the integrated circuits may require class S screening procedure (see Appendix) which offers the highest reliability level of the circuits. However, this class of the screening procedure is very expensive. The required level of reliability should be determined for the DUMAND System components in each of the various subsystems because it has an important bearing on the stress levels and number of tests that should be performed in the component screening procedures. The component screening procedures should be cost effective and should meet time and funding constraints.

Additional improvements in component, and ultimately the DUMAND system reliability, can be realized by applying the techniques of operating a component at a less severe stress than that for which it is rated. Derating is quite effective because the failure rate of most components tends to decrease markedly as the applied stress level and operating temperature are decreased. The DUMAND system components will be operated at an ambient temperature of approximately 0°C which should reduce the component failure rate in comparison with room temperature operation. Instruction for operating procedures are occasionally given in the Military Specifications for different types of components in various applications. Ref. 11 also contains examples of derating instructions for certain electronic components. In the same reference, a detailed discussion is presented on the effects of environmental stress factors on failure rate and also on reliability improvement techniques.

The DUMAND System reliability can be significantly enhanced by designing one or more alternate signal paths through the addition of parallel components or subsystems. A number of approaches should be explored to determine the best redundancy techniques for the DUMAND System. For example, a choice must be made between active and standby redundancy. Standby redundancy is where components are required to detect a failed component, subsystem or signal paths and switch to another path. Active redundancy is where such components are not required. An example of active redundancy is four diodes in series-parallel such that if one diode fails by either open or short circuiting the circuit continues to function. Furthermore, the decision should be made between parallel, voting, nonoperating and operating techniques. The degree of effective isolation of redundant elements must be carefully considered. Isolation is necessary to prevent the failure of one part from adversely affecting other parts of the redundant system. In the DUMAND System, it will be essential that component or subsystem failures in one branch of parallel signal paths cause no more than some allowable degree of degradation of the system performance. The allowable degree of degradation depends on the number of alternate paths available. This approach of allowing a gradual degradation of the System will significantly prolong operating time and it will outweight the space, weight, complexity, cost and time-to-design factors caused by the application of redundancy.

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Appendix

Military Reliability Specifications and Standards for Semiconductor Devices

Semiconductor devices classified as high-reliability types have come to be primarily associated with military and aerospace applications. Although the commercial equipment market is probably the largest user of high-reliability products, military and aerospace agencies, have been largely responsible for the establishment of comprehensive published reliability specifications and standards which have been accepted by the semiconductor industry[15]. MIL standards dominate the procedures used to specify high-reliability semiconductor devices and represent a common reference point frequently used by commercial users to define their requirements.

Military and aerospace requirements for high-reliability semiconductor devices are extremely large and diverse, not only in terms of performance, operating conditions and reliability, but also in terms of logistics and procurements. As a result of these requirements, the military services have jointly developed specifications and standards under which most military end-use semiconductor devices are procured. To simplify procurement, logistics, and the development of reliability data, MIL specs are not issued for the full spectrum of devices manufactured; rather, they are restricted to those devices for which significant need is demonstrated and are specified so that the device can have as wide applicability as possible. Although the limits for operating conditions may exceed those required for some applications, they simplify procurement and assure a supply of devices for the majority of military equipment. These standards also cover a wide range of requirements for the manufacturer on such things as: the procedure and requirements for a manufacturer to become certified to manufacture MIL-spec parts, the requirements for qualifying parts, product-assurance provisions in such areas as quality control, inspection procedures, personnel training, cleanliness, failure analysis and documentation, test methods and procedures, marking and identification of product, and preservation and packing.

A large number of discrete semiconductor devices (e.g. transistors, thyristors, and rectifiers) are covered by published military specifications. Specifications for integrated circuits are relatively new. Most procurements of semiconductor devices for military systems are made by the equipment contractor from MIL-STD parts list. Some military and aerospace programs, because of their size, duration, or special requirements (Minuteman and Apollo are two examples), require that the special specifications and process methods, or even special production lines, be established and tailored to the particular functional, reliability, and economic needs of the program.

Currently, there are two major military specifications used for the procurement of standard semiconductor devices by the military. These specifications are MIL-S-19500F, which covers devices such as discrete transistors, thyristors, and diodes, and MIL-M-38510D, which covers microcircuit products such as monolithic and multichip.

MIL-S-19500F is the specification for the familar Joint Army-Navy or JAN type devices. Detailed electrical specifications are prepared as needed by the three military services and coordinated by the Defense Electronic Supply Center. At present, approximately five hundred detailed electrical specifications are included in the MIL-S-19500F system.

Four levels of reliability, JAN, JANTX, JANTXV, and JANS, are defined by MIL-S-19500F. Devices designated as JAN types receive lot screening only and are the least expensive. Devices designated as JANTX receive some 100% screening (primarily burn-in) and a tight lot-sampling plan. Not all detailed specifications include JANTX requirements. Devices designated as JANTXV are tested the same as JANTX devices; however, they receive an additional visual inspection prior to sealing the package. Only a few detailed specifications include JANTXV testing. Devices designed as JANS requires the manufacturer's certification inspection during manufacturing procedure and quality conformance inspection.

The Defense Electronic Supply Center maintains a "Qualified Products List" of all vendors qualified to produce devices in accordance with MIL-S-19500F. This list is published periodically and is available to manufacturers of military equipment. NASA, to data, has not been a heavy user of MIL-S-19500F, preferring to procure devices to their own specifications.

MIL-S-19500F is the general procurement specification for discrete solid-state devices. and as such it includes MIL-STD-750B, which is the military standard for test methods and procedures for discrete semiconductor devices.

MIL-M-38510D is the military specification for microcircuits. This specification is far more demanding than MIL-S-19500F. MIL-M-38510D also defined three levels (classes S, B, and C) of reliability testing. These levels however, are markedly different from those defined by MIL-S-19500F. Class S, the highest level, is intended primarily for flight and other highly critical applications. Class S devices undergo a lengthy list of 100% screens, plus a tight lot-sampling plan. These devices are intended for applications where maintanance and replacement are extremely difficult or impossible and reliability is imperative. Class B devices are intended for general military usage and undergo less (but still extensive) 100% testing than Class S units. Class C devices undergo the least amount of 100% testing and are, of course, the least expensive.

Approximately 40 detailed specifications are currently included in the MIL-M-38510D system. A Qualified Products List for these devices is maintained by the Defense Electronic Supply Center. NASA is now starting to use MIL-M-38510D specifications.

MIL-M-38510D is the general specifications for integrated circuits, and as such is the parent document for MIL-STD-883B, which is the Military Standard-883B for test methods and procedures and screening tests. MIL-M-38510D, therefore, includes all the methods and procedures of MIL-STD-883B, together with a number of additional quality and administrative constraints.

The additional requirements, as defined by Appendix A of MIL-M-38510D, relate to clearly defined procedures and safeguards to assure the user that the delivered components meet or exceed his specification requirements, personnel training and testing program, inspection of incoming materials, utilities and work in process using on-site facilities, maintenance and cleanliness in work areas, control over changes in design, materials and processes, test equipment maintenance and calibration, and quality-assurance program.

Both MIL-M-38510D and MIL-S-19500F attempt to make available to the designer of military equipment a list of standard, qualified, general-purpose parts which are acceptable to the military. Although MIL-S-19500F and MIL-M-38510D do not cover every semiconductor device available on the market, and do not attempt to do so, enough devices are available to build the majority of military equipment. Use of these devices makes the job of spare-parts inventory far simpler for the equipment manufacturer.

Many semiconductor devices, both discrete types and integrated circuits, are not covered by military specifications, either because they are too new or are not used in sufficient quantities. Many of these devices offer the most recent technological advances or have special performance characteristics which offer advantages to the designer of high-reliability equipment and systems.

Manufacturers cooperate with the users of such products in establishment of high-reliability specifications patterned after military standards that allow these products to be approved for use in military and aerospace systems, as well as in critical industrial and scientific equipment. These specifications form the basis for both the manufacturer's high-reliability devices supplied as custom products and for the manufacturer's slash-series of high-reliability solid-state devices, which are processed and screened in accordance with MIL-STD-883B (integrated circuits) or MIL-STD-750B (discrete devices). Slash-series devices are supplied in several reliability levels (identified by a slash (/) number following the basic device type number) that approximate the Class S, B, or C reliability requirements defined by MIL-STD-883B for integrated circuits or the JAN, JANTX, or JANTXV or JANS requirements defined by MIL-S-19500F for discrete types.

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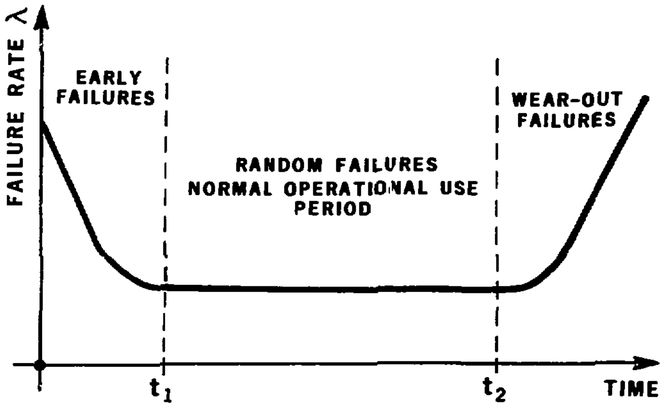

Fig. 1 Typical failure rate characteristics for electronics components.