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MILITARY HANDBOOK

TOTAL-DOSE HARDNESS ASSURANCE GUIDELINES FOR SEMICONDUCTOR DEVICES AND MICROCIRCUITS

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Total-Dose Hardness Assurance Guidelines for Semiconductor Devices AND MICROCIRCUITS

1. This standardization handbook was developed by the Department of Defense in accordance with established procedures and is approved for use by all Departments and Agencies of the Department of Defense.

2. This publication was approved 25 January 1985 for printing and inclusion in the military standardization handbook series.

3. Every effort has been made to reflect the latest information on reliability prediction procedures. It is the intent to review this handbook periodically to insure its completeness and currency.

4. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to Commander, Naval Electronics Systems Command, ATTN ELEX 8111, Washington, DC 20363 by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter

FOREWORD

The purpose of this handbook is to establish a guide for the program manager (PM) and designers of radiation hardened systems.

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APPENDIX

1. SCOPE

The scope of this document is limited to total-dose radiation effects on electronic piece parts. It does not address overall system hardness assurance activities. However, occasionally, specific system requirements may be briefly addressed when it facilitates the discussion.

1.1 Objective. Systems which must operate in a nuclear environment must be capable of nuclear survivability, which means that they shall be able to complete their mission in spite of nuclear stresses. Radiation hardening of a system is the process of ensuring that a system is designed to survive a specific set of nuclear threats. The array of methods and procedures used to make certain that the system achieves the radiation hardness level designed into the system is called radiation hardness assurance (HA). The piece part HA effort not only applies throughout the production phase of the program but extends over the life of the system to ensure that the radiation hardness is not degraded due to operational or maintenance procedures. The HA effort following the production phase is called hardness maintenance (HM).

It is important to understand that piece part HA is performed for a system that has already been designed to survive the specified radiation environment. A major effort in piece part HA of a specific system is the procurement of parts to acceptance criteria developed as part of the original design of the hardened system. Thus, while piece part HA is performed during the production and HM phase of a system, it is an important consideration during the design phase in order to obtain a cost-effective system.

The designers must develop the hardness assurance criteria for those who carry out the piece part HA functions for total dose environments. Therefore, the basic piece part HA requirements are determined by the design function and where applicable require the concurrence of the PM. Although the design function and the HA activities are basically separate entities, the designers must keep the piece part HA procurement costs in mind as they design the system. HA personnel must utilize the requirements established by the design function in order to carry out the piece part HA activities. Consequently, any piece part HA requirements not provided by the design function will need to be determined by HA personnel, using the design guidelines defined in 5.1.

1.2 Document application. This document is applicable to total dose effects on piece parts used in a system in the near earth radiation environments, deep space radiation environments, and the endo- and exo-atmospheric nuclear weapon environments. The following is a brief discussion of the four radiation environments:

a. Near-earth environment (mainly the trapped-radiation belts) can produce a large dose build-up over several years of satellite mission time, with annealing effects normally limiting the damage.
b. Space probe environment (Jupiter) --the total dose is usually accumulated within several hours time, with little annealing during the period of interest. Other environments space probes encounter are the solar wind, solar flares, and cosmic rays.
c. Endo-atmospheric nuclear weapon environment--the total dose is delivered in about 10 seconds, although a significant fraction is accumulated in microseconds. Some annealing does occur.
d. Exo-atmospheric nuclear weapon environment--the total dose is delivered in a very short time period, which provides little time for annealing. In general, for circuits which are not required to operate immediately after the pulse, annealing effects can still be a significant factor (see references 1 through 11).

The different device response from ionizing radiation caused by these environments is due to both the total accumulated dose and the dose rates. For environments with high dose rates (fast total dose deposition), the effects of annealing can be significant. Annealing of the radiation damage is temperature and time dependent. Increasing temperature accelerates annealing, whereas decreasing temperature slows annealing. In either case, annealing effects accumulate with increasing time.

The extent of annealing depends on device fabrication technology and measurement time. It should be noted that while annealing is usually understood to be a reduction of the radiation induced parameter change, there are some integrated circuits which continue to change in the same direction. This phenomenon is sometimes called "reverse annealing".

Selection of a facility to simulate the damage due to these various environments requires careful consideration due to the extreme differences in the associated dose rates and exposure times. In many cases it is important to distinguish between the effects of total dose delivered by gamma rays and by various electrons, though a complete discussion of this distinction is beyond the scope of this document. In general, there have been no observed difference for NPN transistors and for majority carrier devices such as FET's. However, unpublished experimental data taken by the Jet Propulsion Laboratory (JPL) show that 2.2 MeV electrons cause substantially more damage (30 to 60% greater change in $\Delta(1/h_{FE})$ at 150 krads) than an equal dose from Cobalt-60 gamma rays for PNP transistors having a broad range of $f_{T\Delta}$ values. No data is available for comparing electron and gamma irradiation of bipolar integrated circuits, but it is reasonable to expect significant extra damage from the displacement damage induced by relativistic electrons in such devices also. Hence, in radiation testing it is important to ascertain that the radiation source and test timing does, in fact, correctly simulate the radiation environment of interest.

In addition to the above considerations, the electrical bias conditions during radiation exposure can have a very significant effect on device degradation. Degradation can vary depending on bias versus no bias and on whether the bias is negative or positive. The effects of different bias conditions are device-dependent and are further discussed in appendix A.

2. REFERENCED DOCUMENTS

2.1 Government specifications and standards. Unless otherwise specified, the following specifications and standards, of the issue listed in that issue of the Department of Defense Index of Specifications and Standards specified in the solicitation, form a part of this specification to the extent specified herein.

SPECIFICATION

MILITARY

MIL-S-19500 - Semiconductor Devices, General Specification For.
MIL-M-38510 - Microcircuits, General Specification For.
MIL-C-45662 - Calibration System Requirements.

STANDARD

MILITARY

MIL-STD-202 - Test Methods For Electronics and Electrical Components Parts.
MIL-STD-750 - Test Methods For Semiconductor Devices.
MIL-STD-883 - Test Methods and Procedures For Microelectronics.

(Copies of specifications, standards, handbooks, drawings, and publications required by manufacturers in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the contracting officer.)

3. DEFINITIONS

3.1 Definitions. In addition to the definitions specified in MIL-M-38510, the following definitions apply:

3.1.1 Characterization test. The radiation characterization test consists of exposing the test parts to increasing total-dose values until the radiation-induced parameter value, PAR_{RAD}, for each part, passes the specified failure value.

3.1.2 Confidence level. (C) is the probability (usually given in percent) that at least a proportion, P_{DIST}, of the parts in the lot will survive.

3.1.3 Cumulative proportion. (P_{DIST}) is the proportion of a probability distribution which is below a given upper limit (or above a given lower limits). P_{DIST} thus corresponds to an infinite lot size (see 5.1.5.2.2).

3.1.4 Part. Is the electronic part type used in a specific circuit application or test.

3.1.5 Part parameter value. (PAR) is the electrical parameter value measured for a device.

3.1.6 Lot. The collection of parts from which the sample has been taken (see MIL-M-38510).

3.1.7 Lot acceptance test. This term represents the hardness assurance radiation testing of a sample of parts from a procurement lot. It is intended to be a generic term which encompasses tests such as Lot Conformance Tests and Quality Conformance Tests.

3.1.8 Parameter failure value. (PAR_{FAIL}) is the circuit failure value of a particular parameter for the device under evaluation.

3.1.9 Parameter specification value. (PAR_{MIN} or PAR_{MAX}) is the minimum or maximum device parameter specification value prior to irradiation.

3.1.10 Radiation-induced parameter value. (PAR_{RAD}) is the postirradiation parameter value.

3.1.11 Sample size. (n) is the number of parts, selected at random from the lot, which are to be tested.

3.1.12 Measured mean of the logarithms for PAR_{RAD}.

$$\overline{\ln(PAR_{RAD})} = \frac{1}{n} \sum_{i=1}^{n} \ln\left(PAR_{RAD_i}\right)$$

for the log normal distribution where PAR_{RAD_i} is the parameter value measured for the i^{th} device.

3.1.13 Measured standard deviation of the logarithms for PAR_{RAD}.

$$s_{\ln(PAR_{RAD})} = \left\{ \frac{1}{(n-1)} \sum_{i=1}^{n} \left[\ln\left(PAR_{RAD_i}\right) - \overline{\ln\left(PAR_{RAD}\right)}\right]^2 \right\}^{1/2}$$

for the log normal distribution.

3.1.14 One sided tolerance limit factor. (K_{TL}) is calculated for a normal distribution. K_{TL} thus corresponds to an infinite lot size. K_{TL} is a factor such that the probability is C that at least a proportion, P_{DIST}, of the lot will have parameter values less than the mean plus K_{TL} times the standard deviation for parameters increasing with radiation exposure (or P_{DIST} of the total lot will have parameters more than the mean minus K_{TL} times the standard deviation for parameters decreasing with radiation exposure). This statement is illustrated by the following:

$$\ln PAR < \overline{\ln(PAR_{RAD})} + K_{TL} S_{\ln}$$

for parameters increasing with radiation exposure, or

$$\ln PAR > \overline{\ln(PAR_{RAD})} - K_{TL} S_{\ln}$$

for parameters decreasing with radiation exposure. The factor K_{TL} is therefore a function of C, P_{DIST}, and sample size n. Note: PAR_{RAD} is replaced with D_{FAIL} (see 3.17) in the above discussion when K_{TL} is used in fluence to failure calculations.

3.1.15 Parameter design margin.

$$DM = \frac{PAR_{FAIL}}{e^{\overline{\ln(PAR_{RAD})}}}$$

for increasing parameter values, and

$$DM = \frac{e^{\overline{\ln(PAR_{RAD})}}}{PAR_{FAIL}}$$

for decreasing parameter values.

3.1.16 Total-dose. (D) is the total ionizing radiation absorbed dose value under consideration, usually given in Rad(Si) or Gy(Si).

3.1.17 Total-dose circuit failure value. (D_{FAIL}) is the total-dose value for the part under test, which PAR_{RAD} becomes PAR_{FAIL}.

3.1.18 Measured mean of the logarithms for D_{FAIL}.

$$\overline{\ln(D_{FAIL})} = \frac{1}{n} \sum_{i=1}^{n} \ln\left(D_{FAIL_i}\right)$$

for the log normal distribution.

3.1.19 Measured standard deviation of the logarithms for D_{FAIL}.

$$s_{\ln(D_{FAIL})} = \left\{\frac{1}{(n-1)} \sum_{i=1}^{n} \left[\ln\left(D_{FAIL_i}\right) - \overline{\ln D_{FAIL}}\right]^2\right\}^{1/2}$$

for the log normal distribution.

3.1.20 Part categorization criterion. (PCC) equals $e^{K_{TL} s_{\ln(D_{FAIL})}}$ for the parts being categorized. It is used to categorize parts which must be radiation tested.

3.1.21 Total-dose specified value. (D_{SPEC}) is the maximum specified total dose of ionizing radiation which the circuit under consideration must survive.

3.1.22 Total-dose mean failure value. (D_{MF}) equals $e^{\overline{\ln(D_{FAIL})}}$ for the parts being evaluated.

3.1.23 Total-dose design margin. (TDM) equals D_{MF}/D_{SPEC}.

3.1.24 Symbols. (See definitions).

n	Sample size
PAR	Device parameter value
PAR_{RAD}	Radiation-induced parameter value
PAR_{FAIL}	Parameter failure value
PAR_{MIN} or PAR_{MAX}	Parameter specification value
$\overline{\ln(PAR_{RAD})}$	Measured mean of the logarithms for PAR_{RAD}
$s_{\ln(PAR_{RAD})}$	Measured standard deviation of the logarithms for PAR_{RAD}
P_{DIST}	Cumulative proportion of distribution
C	Confidence level
K_{TL}	One-sided tolerance limit factor
PCC	Part categorization criterion
D_{FAIL}	Total-dose circuit failure limit
$\overline{\ln(D_{FAIL})}$	Measured mean of the logarithms for D_{FAIL}
$s_{\ln(D_{FAIL})}$	Measured standard deviation of the logarithms for D_{FAIL}
D_{SPEC}	Total-dose specification value
TDM	Total-dose design margin
TDM(Lot)	Total-dose design margin for lot testing
D_{MF}	Total-dose mean failure value
DM(Lot)	Parameter design margin for lot testing
DMBP	Design margin breakpoint

4. GENERAL TOTAL-DOSE HARDNESS ASSURANCE REQUIREMENTS

4.1 Total-dose radiation testing. For an adequate test to be accomplished, certain key elements are required: a radiation test plan, a test procedure, radiation dosimetry, and suitable radiation facilities. Each of these elements is described below.

4.1.1 Radiation test plan. The test plan defines the process by which the test procedure will be carried out, including: (1) method of test sample selection, (2) type of personnel, organization, and responsibilities, (3) types of facilities to be used, (4) equipment required for measurement and calibration procedures, (5) procedures to be followed, including a step-by-step description of the test (a procedure is required for each separate function performed, including the timing of the post-radiation measurements), (6) documentation, which includes sign-off forms, data format, and identification of the test conditions with the test data, and (7) final data processing and analysis. The test plan must be prepared and reviewed by all principles to ensure that it adequately reflects the system requirements. The individual test procedures are developed from this test plan. For total-dose cobalt 60 and electron tests, MIL-STD-883 or MIL-STD-750, test method 1019 should be specified.

4.1.2 Radiation test procedure. The radiation test procedure is a complete description of the requirements for a single device type. The major areas to be defined by the procedure include, but are not limited to: (1) a description of the devices to be irradiated, such as part type number, package type, number of leads and pin out, serial numbers, and lot and wafer numbers; (2) bias conditions of the device, and operating conditions during the radiation exposure; (3) the specific radiation facility and the radiation total dose and dose rate for each exposure, (4) the electronic parameter preirradiation values and test conditions, (5) the bias circuit diagrams showing the location of all circuit elements during each measurement; (6) whether or not the test is to be made in-situ, (7) the electronic parameter measurements required and the device operating conditions during measurements, (8) a list of all test fixtures and test equipment or equivalent required for the test, (9) the format in which the data is recorded. The test procedure must be prepared and reviewed by all principles in the system to ensure that it adequately reflects the needs of the data user.

4.1.3 Radiation dosimetry. Test data may not be valid without considerable attention to obtaining correct radiation dosimetry. While there are a number of reasonably valid techniques, the most commonly used system is thermoluminescent dosimetry (TLD). The ASTM and DoD have recently approved a standard for use of TLD dosimetry in radiation testing, ANSI/ASTM E668-78, "Standard Practice for the Application of Thermoluminescence - Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation Hardness Testing of Electronic Devices." This standard gives considerable detail on correction procedures. Additional dosimetry information may be obtained from references 12 and 13.

The dosimetry shall be used to calibrate each location used for exposure of test devices to within ±10 percent accuracy. The calibration shall be traceable to National Bureau of Standards accuracy. If an area is to be used for an array of samples, the uniformity of the field shall be determined The field used should be uniform to within 15 percent, for most applications. The source decay must be calculated and applied at least every two months.

The cobalt 60 sources, which are in common use for testing electronic parts, vary in geometry of the shielding (lead or water) that is near the source In parts testing, when heavy shielding is near the source, the gamma ray spectrum is seriously altered, resulting in a large low-energy component of (back scattered) gamma rays. The low-energy gammas can produce dose enhancement effects in device package materials and other high z elements used in device construction such that the actual dose absorbed in the radiation-sensitive region of a device can be different from Cobalt 60 sources having different energy spectra. These differences may be as much as a factor of 2 in some practical cases. Factors of 30 percent variations are most likely common experience.

For particle accelerators, the radiation fluence or dose must be measured for each exposure with an appropriate method, such as a Faraday cup or with TLD. This practice is required because the flux may vary radically for each exposure with such sources.

4.1.4 Radiation facilities. Selection of the correct type of radiation facility is one of the most important aspects of total-dose radiation testing. This choice depends on the type of radiation sources to which the system is to be exposed. For some nuclear weapon environment simulations, total-dose pulsed sources should be considered to analyze the annealing function for short radiation times. For residual contamination and for space-radiation applications, cobalt 60 or steady-state electron accelerators are used at various dose rates that are considered applicable.

4.2 Hardness assurance provisions. In order that the piece part HA effort be properly carried out, specific information must be provided to the production and HM activities. This information is generated by the design function and is provided to the production and maintenance personnel as part of the system Hardness Assurance Design Documentation (HADD). As a minimum, the following information needs to be provided for each part type so that the piece part HA activities can be properly carried out:

a. Total-dose specified value, D_{SPEC} (see 5.1.8.1).
b. Total-dose radiation test requirements per MIL-STD-883, method 1019.
c. For each lot acceptance test, the following information is required for both the testing-by-attributes and testing-by-variables methods (see 5.1.8.1.1 and 5.1.8.1.2):
   (1) Part type, vendor identification, and parameter description.
   (2) Bias conditions during irradiation.
   (3) Operating conditions during electrical parameter measurements. Indicate if measurements are in-situ or not.
   (4) Any other special setup or test requirements.
d. The following additional information is required for the testing-by-variables method:
   (1) The value of the one-sided tolerance limit factor, K_{TL}, the cumulative proportions of distribution, P_{DIST}, the confidence level, C and the sample size, n (see 5.1.8.1.2).
   (2) Whether the test is at a single fixed total-dose or multiple total-dose to failure (see 5.1.3.2).
   (3) The total-dose level or levels for conducting the test.
   (4) Parameter failure value, PAR_{FAIL}. Indicate if parameter increases or decreases with radiation exposure (see 5.1.3.2).
e. The following additional information is required for the testing-by-attributes method.
   (1) The minimum or maximum parameter value for lot acceptance.
   (2) The Lot Tolerance Percent Defective, LTPD, value (see 5.1.8.1.1).
   (3) The failure acceptance number if other than zero (see 5.1.8.1.1).
f. When lot acceptance testing is not specified, part applications that require occasional sample testing should be indicated (see 5.1.5.3). The requirements of (3) above must be furnished if sample testing is required.

5. DETAILED TOTAL-DOSE HARDNESS ASSURANCE REQUIREMENTS

5.1 Radiation design hardening. This section presents the system radiation design hardening activities which are necessary to develop a piece part hardness assurance (HA) program. These activities include worst case circuit analysis, radiation testing, and characterization of the parts, determining whether the part type requires HA lot acceptance testing, and providing the information necessary to carry out the HA program. This HA information is required to ensure that the radiation hardness designed into the system is maintained during production and any future reprocurement of piece parts. Figure 1 is a flow diagram of a typical system piece part total-dose design and HA plan (see 5.1.5 for an explanation of hardness critical category IM and hardness critical category 2).

Piece part radiation hardness criteria developed during the system design are essential to a cost-effective HA program. They are also instrumental in establishing the cost level of the HA activities throughout the life of the system. The goal in design is to select parts and design the circuits so as to minimize the total HA costs, including lot acceptance testing. For example, it may be less costly in the long run to specify a more expensive radiation hard part type or to increase the complexity of a circuit if it allows the elimination of requirements for lot acceptance testing. This section provides guidelines for establishing piece part HA requirements during the system design phase so as to meet these goals.

In order to carry out these requirements properly, it is necessary for the design function to specify the method that will be used to determine if HA lot acceptance testing will be required for the part procurement activity. There are two methods recommended. One is called the design margin breakpoint method (DMBP), in which a single number, called the breakpoint value, is used as the criterion for determining if HA testing is required. This single number generally applies to all part types (see 5.1.5.2.1). Additional details regarding the DMBP method are contained in the Air Force Weapons Laboratory document AFWL-TR-76-147, and the reader is referred to this document for a further discussion of this method. The second method is called the part categorization criteria method (PCC) in which the criteria are determined separately for each part type by analyzing the radiation characterization data (see 5.1.5.2.2).

For systems where the radiation environments are not severe the DMBP method of categorizing the parts (described in 5.1.5.2.1) should be considered. However, where the radiation environments are more severe, the PCC method (discussed in 5.1.5.2.2) is more appropriate. It should be pointed out that both methods require radiation characterization testing and determination of the Total-Dose Design Margin (TDM). The basic difference between the two methods is that the PCC method requires calculation of the PCC value for each part using the characterization test data, whereas the DMBP usually applies a single criterion to all parts.

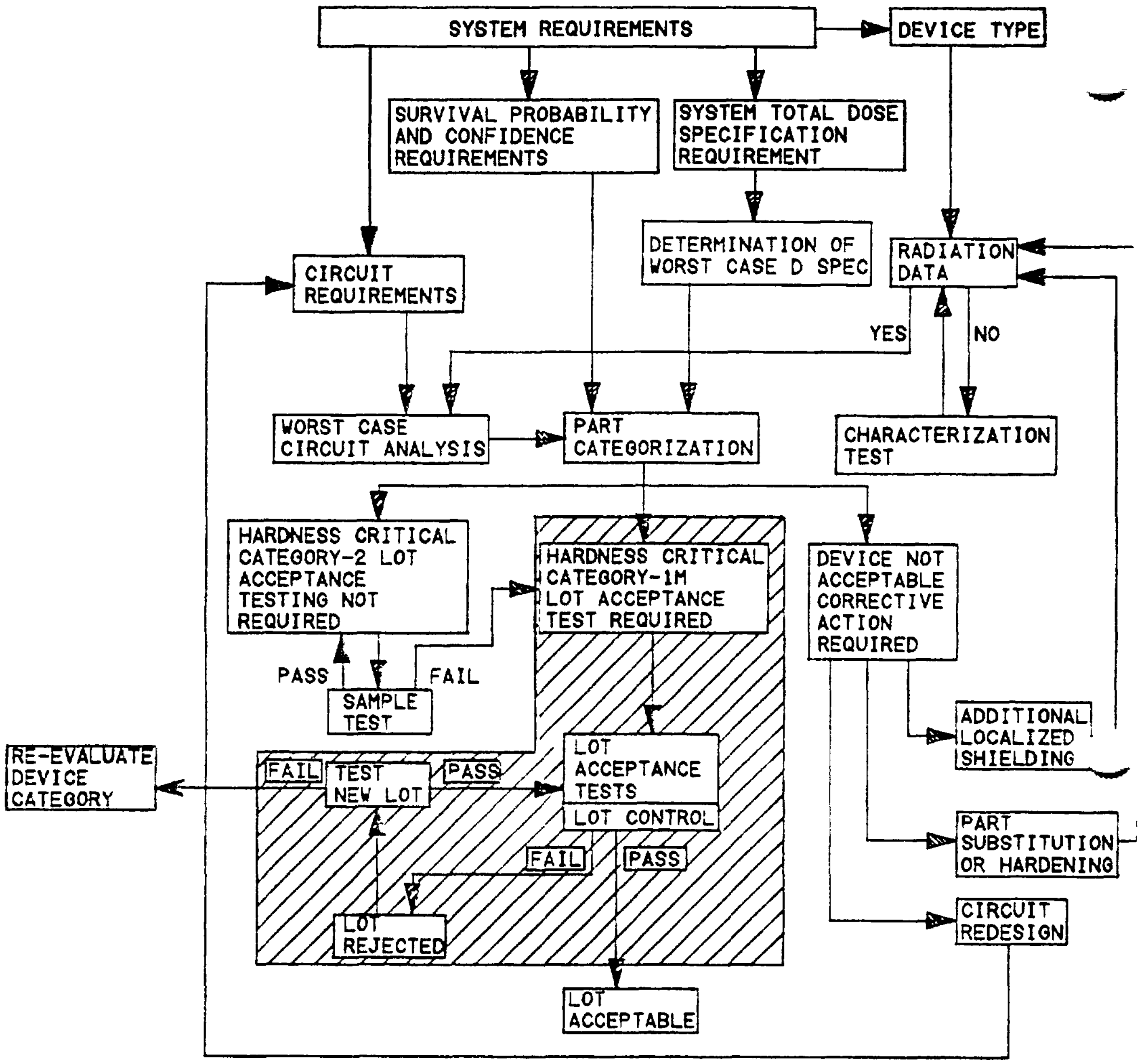

FIGURE 1. A typical system piece part-total dose design and hardness assurance plan (HA function in shaded area)

The design activity should also specify whether the lot acceptance testing will use a lot tolerance percent defective (LTPD), i.e., testing-by-attributes, or a testing-by-variables method. These tests methods are further discussed in 5.1.8.1

It is intended that the piece part HA requirements generated during the system design phase provide sufficient information so that the HA activities can be carried out during the production phase of the program, including the procurement of piece parts, and during subsequent deployment and maintenance of the equipment without the necessity of additional design type activity. Consequently, it is imperative that the information be provided to the HA function as part of the Hardness Assurance Design Documentation (HADD). As a minimum, the information should cover the items specified in 4.2. Otherwise, it may be necessary for the HA function to develop the missing piece part HA information during the production phase of the program, a result which is redundant and may omit critical design considerations.

Although this document is intended to provide the necessary steps for developing a piece part total dose HA program, it is highly desirable that additional detailed guidance be obtained from a radiation effects specialist as early in the design stages of the program as practicable. Such a specialist can be helpful in providing current radiation effects information regarding parts application and selection, and can serve as a consultant for the many special problems that arise during the development of a HA program. Additional guidance may also be obtained by contacting government agencies such as the Army's Harry Diamond Laboratories, Adephi, Maryland; the Air Force Weapons Laboratory, Albuquerque, New Mexico; or the Naval Weapons Support Center, Crane, Indiana.

5.1.1 Parts selection. One of the most-cost effective steps in a piece part HA program is the proper selection of radiation-resistant parts. Because there are as yet no reliable electrical correlations for predicting the radiation sensitivity of electronic parts in a total-dose environment, the main reliance for HA must be placed on costly lot acceptance testing. Therefore, every effort must be made to select parts which do not require lot acceptance tests.

In the total-dose radiation environment, vendor selection is very important. Radiation test results indicate that certain vendors produce parts that are harder than others for the identical part type. In addition, there is no correlation between vendors as to the radiation sensitivity for a given part type. For example, if the results of a radiation test indicate that a certain vendor's transistor need not be lot acceptance tested, it cannot be assumed that the same transistor type from a different vendor need not be lot acceptance tested. This means that in many cases, a vendor must be considered as sole-source (see 5.1.5) for procurement purposes, unless additional vendors can be qualified. An exception to this may occur for systems with moderate total-dose requirements (see 5.1.7). It is important to note that, because total-dose sensitivity is highly process-dependent, even a qualified vendor's line may change. This is why occasional sample testing of parts which have been qualified as acceptable is recommended.

5.1.1.1 Unacceptable parts. As has been previously mentioned, part types with very low design margins should be eliminated from use in the system. The decision as to when a design margin is low enough to make the part unacceptable will depend on the cost of rejecting lots during hardness assurance versus the cost of either using a harder part type or re-designing the circuit. Since these costs are highly dependent on the specific part type and the specific system in which it is used, no one formula for determining a minimum acceptable design margin will apply to all situations. Two suggested general rules are:

a. Part types with design margins less than one should not be used.
b. Part types with design margins between one and two should only be used if no alternatives are available. On the basis of calculations for silicon bipolar transistors, a high rate of lot rejection and/or part failure is to be expected when parts with design margins less than two are used.

The HADD, of course, will not contain an acceptable part category since it only list parts which are used in the system.

5.1.1.2 Parts sensitivity up to one megarad. The following discussion of the radiation sensitivity of electronic part types is limited to a steady state, total-dose environment where the Total-Dose Specified Value, D_{SPEC}, does not exceed one megarad(Si). This limit applies only to the following discussion and does not imply that D_{SPEC} may not exceed one megarad for some specific system applications.

With the exception of special, extreme-precision circuit applications, the following non-semiconductor part types can be considered as non-radiation sensitive parts, without further radiation testing or concern:

a. Capacitors
b. Resistors
c. Magnetic devices
d. Electro-mechanical devices

The following semiconductor part types, except for high-precision applications, do not normally require lot acceptance testing. However, they may require occasional sample radiation testing as discussed in 5.1.5.3.

a. Diodes, such as switching and rectifier diodes
b. Digital bipolar microcircuits such as I^2L, T^2L, LSTTL, STTL, and ECL (except for bipolar devices made with new sidewall oxide isolation techniques - for example IMOX, FAST, AS and ALS)

With the above exceptions, the radiation sensitivity of other semiconductor part types should be thoroughly evaluated on the basis of existing radiation test data when available. If a data base is not available, it will be necessary to generate the radiation test data by means of characterization testing. Certain part types, such as linear operational amplifiers and unhardened MOS, are very sensitive to total-dose radiation, even at levels well below one megarad(Si).

5.1.2 Circuit hardening. Circuit hardening can be a very cost-effective approach to radiation hardening. The subject is complex, and a complete treatment is beyond the scope of this document. However, some typical hardening techniques and examples are presented below:

a. Circuits should be designed to maximize the use of non-sensitive parts. For example, bipolar digital logic may be used instead of commercial CMOS logic, provided of course that power requirements permit.
b. Vendors with a history of providing commercial (nonhardened) parts that are radiation resistant should be selected.
c. Circuit design should minimize the sensitivity of critical parameters, i.e., transistors should be operated at the collector current value that maximizes gain, and output drive current should be distributed so that it is adequate after irradiation.
d. Radiation-hardened parts should be specified when nonsensitive parts cannot be utilized

These are some of the typical methods used to increase circuit radiation resistance. A further discussion of radiation sensitive parameters and additional circuit application information are contained in Appendix A. When circuit hardening techniques are applied in space systems, the amount of circuit hardening required may vary, depending on the location of the part in the equipment. This is due to the inherent shielding provided by the material surrounding the part for the charged particle environment in space.

5.1.3 Radiation characterization. Radiation test data are necessary for a characterization of parts in a total-dose radiation environment. When one is available it is cost effective to use an existing data base. Otherwise, it will be necessary to perform radiation characterization tests. Evaluation of radiation test data by different industry and government facilities indicates that most radiation test data is best represented by a log normal distribution. Therefore, the log normal distribution may be assumed unless the data shows the distribution to be non-log normal.

It is best not to use the characterization data to extrapolate survival probabilities to high confidence levels unless a large sample size (minimum of 25 devices) is used and the exact distribution is determined by means of a statistical test such as the Chi-square goodness-of-fit test.

It should be noted that the selection of the sample size is a trade-off between the cost of characterization testing and the cost of additional lot acceptance testing during the procurement phase of the program. Although a small sample size reduce the cost of characterization testing, it will increase the value of K_{TL} and consequently the value of PCC (see 5.1.5.2.2). As can be seen from figure 4, a higher value of PCC may increase the number of devices that require expensive lot acceptance testing during future procurements. This trade-off should be considered prior to the selecting of a sample size for the characterization tests. Where practicable, a minimum sample size of ten devices is recommended.

5.1.3.1 Existing data base. In order for existing data to be acceptable for characterizing a device, the data should meet the following requirements:

a. The part, vendor, and bias conditions during radiation testing and parameter measurement should be the same as those used in the worst case circuit analysis.
b. The radiation test environment should be the same as or acceptably close to the environment given as the system requirements.
c. The data should be in a format that permits an evaluation of the parameter change versus total dose at a minimum of three radiation levels.
d. The highest radiation level should be at least twice the total dose specification value, D_{SPEC}, to allow verification that the part behavior is not beginning to change rapidly just above this level.

If the above conditions cannot be met, it will be necessary to perform a characterization test in order to generate the necessary data. Some bases of existing data may be of use. See, for example Electronic Radiation Response Information Center, operated for DNA by Kaman-Tempo, P.O. Drawer QQ, Santa Barbara, CA 93102.

5.1.3.2 Characterization testing and data analysis. The radiation characterization test consists of exposing the test parts to increasing total-dose values until the radiation induced parameter value, PAR_{RAD}, for each part, passes the specified failure value, PAR_{FAIL}. PAR_{FAIL} is determined from a worse case circuit analysis, as described in 5.1.4. The PAR_{RAD} versus total-dose values are plotted on graph paper, including a horizontal line representing the failure value, PAR_{FAIL}. The total-dose value for each part is then scaled from the abscissa at a point directly below where the PAR_{RAD} curve intersects the PAR_{FAIL} line. This total-dose value is called the Total-Dose Circuit Failure Value, D_{FAIL}. These D_{FAIL} values are used for categorizing the part types and establishing the piece part HA criteria. An example of plotting the characterization test data is shown on figure 2 for the case where PAR_{RAD} increases with radiation exposure.

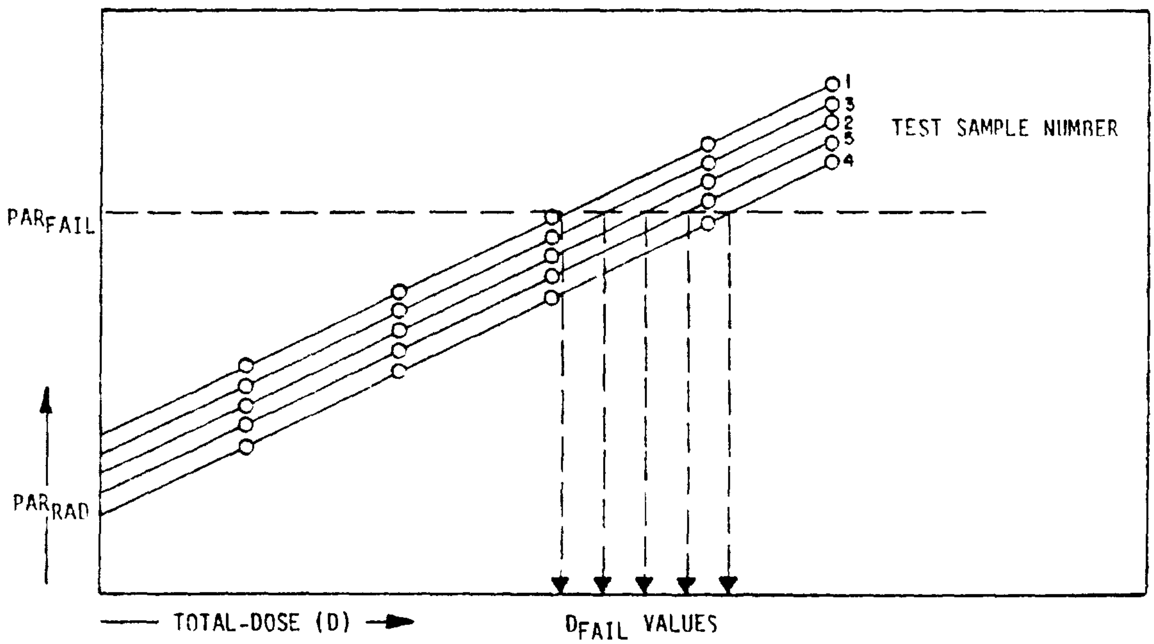

FIGURE 2. Relationship of factors used for determining D_{FAIL}.

In addition to being used for determining the D_{FAIL} values, the shape of the data plots is evaluated in order to determine if the HA lot acceptance test should be a single dose type test, at the Total-Dose Specified Value, D_{SPEC}, or a multiple total-dose to failure type test. If the data plots are approximately linear, the HA lot acceptance tests sxhould be performed at a single total-dose value, D_{SPEC}. However, if the shape of the data plots varies significantly from a linear shape, a multiple total-dose to failure type of HA testing is preferable (see 5.2.2). Whenever possible, HA testing should be performed at a single total dose value, because testing at multiple doses is more costly.

Occasionally when characterization tests are conducted, all of the parameter values may not reach PAR_{FAIL}, even when the test total-dose values are much higher than D_{SPEC}. In this case, a minimum of five test parts should reach PAR_{FAIL} if the test is to be meaningful.

The requirements for conducting the radiation characterization test are defined in MIL-STD-750 or MIL-STD-883, test method 1019, and in 4.1. As part of these requirements, the following recommendations are offered.

a. Sample size: A randomly selected sample size of 10 parts is recommended as a minimum (see 5.1.3).
b. Bias conditions: The bias conditions during radiation testing and measurements should be the same as those used in the worst case circuit analysis.
c. Total-Dose Levels: The parts should be measured after each irradiation, at a minimum of three radiation levels. The radiation test levels should extend from below the D_{SPEC} value to a level where PAR_{RAD} intersects or exceeds the PAR_{FAIL} line. In addition, one of the test levels should be at D_{SPEC}.

5.1.4 Worst case circuit analysis. A worst case circuit analysis of each circuit in the system is required for a determination of PAR_{FAIL} and for an evaluation of the circuit induced system susceptibility to the radiation environment. This analysis is normally performed at the D_{SPEC} total-dose value. There can be different levels of worst case circuit analysis,depending on the system requirements. Worst-case circuit analysis requires a knowledge of the (1) device types to be used, (2) radiation sensitive parameters, (3) radiation response of the surrounding parts, and (4) circuit operating requirements, including temperature derating and aging. With these inputs, under the worst-case circuit conditions (frequency, bias, temperature, etc.), a maximum or minimum end-point electrical-parameter failure value, PAR_{FAIL}, is determined, this value is known as the circuit failure value for the device parameter under evaluation. After total-dose irradiation, this failure value cannot be exceeded without causing circuit failure. Whether PAR_{FAIL} is an upper value or a lower value should be indicated.

For each radiation sensitive device type one electrical parameter must be selected as being of primary interest. These are the parameters most sensitive to the radiation environment and are, therefore, the most critical to circuit requirements and make up the bulk of data available in the radiation effects data banks. In addition to these primary parameters, other parameters could be critical for special or unusual device applications. These special parameters may or may not be radiation sensitive, and each case must be evaluated individually. (This subject is further discussed in Appendix A). It should be noted that there can be more than one value of PAR_{FAIL} for a given parameter for devices used in different circuit applications. However, only the worst case parameter value should be used for a given part type.

5.1.5 Part categorization. As part of the design activities, it is necessary to determine the radiation response of the part types and to identify those part types that will require lot acceptance testing. This is done by categorizing the part types in accordance with 5.1.5.2. The following categorizations are defined:

Hardness Critical Category 1M (HCC-1M) - Lot acceptance tests required.

Hardness Critical Category 1H (HCC-1H) - These parts do not require lot acceptance tests, but are included in the HCC-1 classification because they are hardness dedicated parts.

Hardness Critical Category 1S (HCC-1S) - These part types do not require lot acceptance tests, but are included in the HCC-1 classification because each is a sole-source part types that must be obtained from one or more specific manufacturers due to its process-related radiation characteristics. HCC-1S parts may require occasional sample testing similar to that done for HCC-2 part types (see 5.1.5.3).

Hardness Critical Category 2 (HCC-2) - These part types do not require lot acceptance tests, but they may require occasional sample testing.

Hardness Non-Critical (HNC) - These parts have such large design margins that they require no testing even on an occasional basis (TDM > 100).

The HCC-1H application is used for parts that are designed into circuits as hardness dedicated parts. The sole function of these parts is to protect the circuit from specific radiation responses. HCC-1S is used for sole-source parts where the radiation characterization tests indicate that this is the only manufacturer tested whose part meets the radiation response requirements of the system. Both the HCC-1H and HCC-1S are included in HCC-1 for systems HA parts control purposes only.

Before the methods used to determine the part categorization are presented, it should be pointed out that the majority of radiation test data is best represented by the log normal distribution. This may cause the methods described to appear unfamiliar to readers who are more familiar with analysis methods using normally distributed data. The log normal distribution is nonsymmetrical with a positively skewed tail. The average value is the geometric mean and the variance of the data is the geometric dispersion. In order to apply normal statistical calculations to log normal data, it is first necessary to transform the data into a normal distribution by taking the log values of the data. After the normal statistical calculations are completed, the antilogs must be used to transform the calculations back into the log normal form.

5.1.5.1 Total-dose design margin. In order to calculate the Total-Dose Design Margin, TDM, it is necessary to determine the Total-Dose Mean Failure Value, D_{MF}, from the characterization test data. D_{MF} is calculated, using the PAR_{FAIL} values, as follows:

eq. 5.1.1

$$D_{MF} = e^{\overline{\ln(D_{FAIL})}}$$

where

$$\overline{\ln(D_{FAIL})} = \frac{1}{n} \sum_{i=1}^{n} \ln\left(D_{FAIL_i}\right)$$

and D_{FAIL_i} is defined as the total-dose circuit failure value for the i[th] device.

D_{FAIL} is simply the dose value where each part reaches the parameter failure value determined by the worst case circuit analysis.

TDM can then be calculated as the ratio of D_{MF} to the Total Dose Specified Value, D_{SPEC}, which the circuit must survive. Therefore,

$$TDM = \frac{D_{MF}}{D_{SPEC}}$$

and relates the part total-dose response to the specified system radiation requirements.

In spacecraft systems, D_{SPEC} is often lower than the system total dose specification because of the shielding provided to the circuit by the box in which it resides and the surrounding materials of the total system. In such cases, D_{SPEC} is calculated with a computer program. If detailed information about the surrounding masses is not known, then the proper procedure is to use the system specification total-dose value as D_{SPEC}.

As pointed out in paragraph 5.1.3.2, occasionally less than three parts have their parameters reach PAR_{FAIL}, in which case the data analysis is not considered meaningful and TDM cannot be determined by the method defined above. In this case the special methods described in 5.1.5.2.1 and 5.1.5.2.2 should be used.

5.1.5.2 Part categorization methods. Part categorization is used in order to determine if HA lot acceptance testing is required for a particular part type. There are two methods proposed for classifying the parts. Both methods require radiation characterization testing of a sample of parts in order to determine TDM, and then a comparison of TDM to a numerical value. The first method is called the Design Margin Breakpoint (DMBP) method, where TDM is compared to the DMBP value. The DMBP value is specified by the design function and applies equally to all applicable part types. The DMBP method is generally used where the radiation environment is not severe. In the second method, TDM is compared to a number determined separately for each part type by analyzing the individual radiation characterization test data. This second method is called the Part Categorization Criteria, PCC, method and is generally indicated for more severe total-dose requirements where the part survival probabilities are low. Depending on the overall system requirements, the approach to categorizing the parts can be modified to include several DMBP values or a combination of the DMBP and PCC methods. For example, one DMBP value could be used for less sensitive part types and a second value or the PCC method could be used for the more sensitive part types or parts used in very critical applications.

In addition to the DMBP and PCC values, the design function must specify a number that is used between unacceptable and HCC-1M. The value assigned this number must be based on several considerations. A small value is desirable in order to minimize the number of part types categorized as unacceptable. However, a small value may result in an unacceptably high rejection rate during lot acceptance testing for part types with small design margin values. For the examples of figures 3 and 4, a value of 2 is used.

5.1.5.2.1 Design margin breakpoint method. The DMBP method is generally specified for systems with moderate total-dose requirements (see 5.1.7). When the DMBP method is used, the value of the DMBP number is specified by the design function. This number is the breakpoint between HCC-1M where tests are required on each lot and HCC-2 where tests are not required on each lot.

The DMBP value is generally selected to represent a specific survival probability and confidence level. Increasing this value increases the confidence that can be placed in the HCC-2 part selection. However, it also increases the number of HCC-1M part types that will require lot acceptance testing. Generally, it is cost effective to set the DMBP value as low as practicable within the risk factors established by the system requirements. An example of determining the DMBP value is given in Appendix B. Figure 3 shows these relationships. When a part type has been categorized as unacceptable, the corrective methods of 5.1.6 should be considered.

5.1.5.2.2 Part categorization criteria method. The PCC method is generally specified for systems with stringent total-dose requirements. When the PCC method has been specified for categorizing the part types, it will be necessary to calculate the PCC values based on the characterization data. PCC is used to differentiate between HCC-1M and HCC-2. Figure 4 shows these relationships. When the classification is unacceptable, the corrective methods of 5.1.6 should be considered.

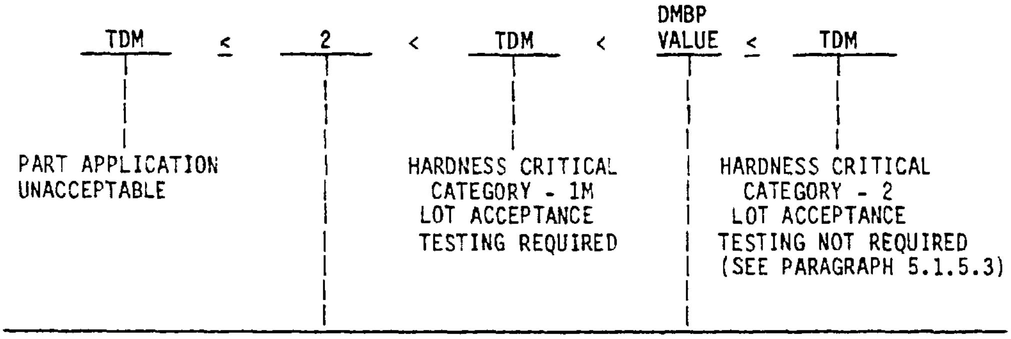

FIGURE 3. Example of a relationship between TDM and the DMPB value.

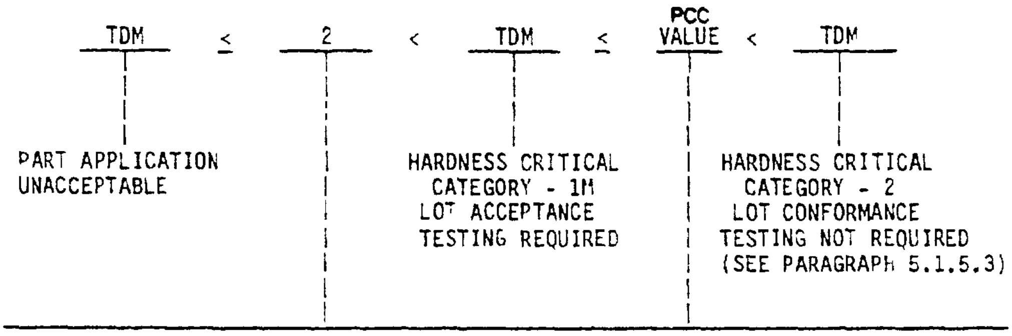

FIGURE 4. Example of a relationship between TDM and the increasing PCC values.

Before the method used for determining the PCC value is presented, a discussion of the factors used in the calculations are in order. The discussion will include the variability of the characterization total-dose failure values obtained during characterization, a confidence factor, and the required survival probability.

The variability of the data is represented by the standard deviation, s, and is calculated using the D_{FAIL} values described in paragraph 5.1.3.2. Because we are dealing with the log normal case, this factor is represented as the Total-Dose Sample Standard Deviation, $s_{\ln(D_{FAIL})}$, which is the standard deviation of the logs of the D_{FAIL} total-dose values and is calculated as follows:

$$s_{\ln(D_{FAIL})} = \left\{ \frac{1}{(n-1)} \sum_{i=1}^{n} \left[\ln\left(D_{FAIL_i}\right) - \overline{\ln\left(D_{FAIL}\right)} \right]^2 \right\}^{1/2} \qquad \text{eq. 5.1.2}$$

where D_{FAIL_i} is the total-dose circuit failure limit for the i^{th} device and n is the sample size.

The level of confidence and the survival probability are introduced into the calculations by multiplying $s_{\ln(D_{FAIL})}$ by the factor K_{TL}.

The factor K_{TL} is called the one-sided tolerance limit and is selected from a table of tolerance limits (see Appendix B and reference 14). This factor K_{TL} is a function of the sample size, n, proportion of the distribution, P_{DIST}, and confidence level C. The theory may be further explained as follows: if the characterization test were repeated many times, 90% of the time (90% confidence) 99% of the PAR_{RAD} values would be equal to or less than the mean plus K_{TL} times the standard deviation, s, or $\bar{X}$ + 3.532s.

We will not present the method for calculating the PCC value using the $s_{ln(D_{FAIL})}$ and K_{TL} factors previously discussed where

$$PCC = e^{K_{TL} s_{ln(D_{FAIL})}} \qquad \text{eq. 5.1.3}$$

Increasing P_{DIST} and C, and consequently K_{TL}, increases the PCC value and the cost of the HA program. This is because increasing the value of PCC increases the number of part applications that will be categorized as HCC-1M requiring expensive lot acceptance testing. Increasing the sample size, n, generally will increase the cost of the characterization test. However, this added cost may be more than offset during the HA phase of the program, because increasing the value of n results in a lower value of K_{TL} which in turn may reduce the number of part types requiring lot acceptance testing. As can be seen, the values of P_{DIST}, C, and n selected are a trade-off between the level of HA desired and the amount of funding available for the HA program. The values of P_{DIST}, C, and n need to be specified by the design function when the PCC method is used. Several examples of determining the PCC values and categorizing part applications are given in Appendix B.

5.1.5.3 Sample testing. A part type classified as HCC-2 does not require lot acceptance testing. However, where the TDM value is less than 100 a sample test should be conducted at least once each six month period during parts procurement unless otherwise specified. The selected value of 100 is based on past experience and engineering judgement; however, the number should be revised if special system requirements so indicate. A sample test consists of randomly selecting a few samples from a parts procurement, radiation-testing of the parts, and analyzing the data to ensure there have been no significant changes in the radiation sensitivity of the part type. If significant changes are indicated, the part categorization should be re-evaluated.

5.1.6 Corrective action. When a part type is not acceptable, several methods may be used to address the problem (1) a substitute part type may be used, (2) the circuit can be redesigned, or (3) localized radiation shielding can be added for space radiation cases.

5.1.6.1 Part type substitution. As previously explained, there can be an extreme variability in radiation sensitivity between different manufacturers and part types. Consequently, it is sometimes possible to upgrade an unacceptable classification to HCC-1M or a HCC-1M to HCC-1S by categorizing the same part type using a different manufacturer or specifying a harder part type. This is a very cost-effective method of improving the radiation hardness of the circuit. However, the substitute part type must be evaluated by characterization testing prior to being used.

5.1.6.2 Circuit redesign. The circuit design should be re-evaluated in order to investigate the feasibility of redesign so as to decrease the sensitivity of the part application (see 5.1.2).

5.1.6.3 Radiation shielding. By adding localized radiation shielding around a part, the total-dose radiation level can (in space radiation cases) be reduced sufficiently to allow the part type to be upgraded, depending on the part sensitivity and the radiation type and energy spectrum. Adding shielding is normally a cost-effective way to harden the system when a few radiation sensitive part types are used, provided the system design limits can tolerate the additional weight of the shielding material. However, such parts must be re-characterized for the lower total-dose level and categorized as HCC-1M because the lot acceptance testing dose level may be different from that of non-shielded parts. For systems with nuclear weapon environmental requirements, shielding is most often impractical due to the high penetration of the nuclear radiation.

5.1.7 Systems with moderate total-dose requirements. The following discussion is limited to systems with moderate total-dose requirements such as encountered in manned aircraft or ground equipment. Under these circumstances, most electronic piece parts are not a total-dose radiation problem; notable exceptions are parts such as unhardened metal-oxide-semiconductors (MOS), and large and very large scale integrated circuits (LSI and VLSI) which can be sensitive at very low levels of total-dose radiation (see 5.1.1.1 for a further discussion of this subject). For moderate total-dose levels, except for very sensitive part types such as previously discussed, sole-source procurements may not be necessary and other qualified vendors should be evaluated as second sources.

Generally, for systems with moderate requirements, either the breakpoint method of categorizing the parts applications (see 5.1.5.2.1) or the attributes method of lot acceptance testing (see 5.1.8.1.1) should be considered for the majority of parts. If very sensitive parts are used in the system, the PCC method of categorizing the part type (see 5.1.5.2.2) and the variables method of lot acceptance testing (see 5.1.8.1.2) should be applied.

5.1.8 Hardness assurance considerations. The most cost-effective approach to piece-part HA is to determine the requirements once during the design phase of the program and then to use these same requirements for all future HA parts procurement activities. For this to be done effectively, the piece part HA requirements must be complete and be included as part of the HADD information, so that no additional design activity or part characterization is required during the system production and HM procurement phase of the program.

5.1.8.1. Hardness assurance testing. In order to minimize the amount of radiation HA testing, all applications for a given part type parameter should be evaluated at a single total dose, using one radiation lot acceptance test. This can normally be done by using the worst case bias conditions during irradiation. The details of how this is done needs to be specified and included as part of the HADD information furnished the HA activity.

5.1.8.1.1 Testing-by-attributes. In order to perform the HA lot acceptance testing, it is necessary for the design activity to specify the method to be used and the lot acceptance criterion. For systems where the required part survival probabilities are low a testing-by-attributes, Lot Tolerance Percent Defective (LTPD) method using a zero acceptance number as described in Appendix B of MIL-M-38510 should be considered. Table XV, Appendix B of MIL-M-38510, lists the minimum size of samples to be tested to assure, with 90 percent confidence, that a lot having percent defective equal to the specified LTPD will not be accepted. The accept-reject criterion normally is determined from the characterization test data and the worst case circuit analysis.

5.1.8.1.2 Testing-by-variables. Where the required part survival probabilities are higher, the testing-by-variables method is more appropriate. Since testing-by-variables makes greater use of the information concerning the lot than does testing-by-attributes, the variables method provides higher confidence and survival probability for a given sample size. It should be pointed out that both the attributes and variables test methods require radiation lot acceptance testing. The basic difference between the two plans is that the variables plan requires that the accept-reject criterion be calculated from the lot acceptance test data. Several examples of testing-by-variables are given in Appendix B of this document.

5.1.8.2 Hardness assurance information. As a minimum, the information given in 4.2 needs to be specified by the design function so that the piece part HA activities can be properly carried out. This information is normally supplied as part of the HADD package.

5.2 Piece part radiation hardness assurance. This section provides the necessary information for carrying out the piece part radiation activities of a HA program, provided the provisions of 4.2 are documented by the system design function as part of HADD. The piece part HA program is intended to ensure that the system retains the radiation hardness level designed into it and is carried out during the production phase and piece part procurement for the hardened system. However, if all of the design phase HA requirements (listed in 4.2) are not provided, it will be necessary for the HA function to supply the missing requirements on the basis of the methods of 5.1.

5.2.1 Lot acceptance criterion for testing-by-attributes. This criterion is either a maximum or minimum parameter value provided by the design function. In the case of a maximum value, the entire lot of parts is rejected if one test sample exceeds it. In the case of a minimum value, the entire lot is rejected if one test sample is less than that value.

5.2.2 Lot acceptance criterion for testing-by-variables. (At this point it is suggested that the reader review the symbols and definitions in section 3 and the procedures of 5.1 before continuing. Also, examples are given in Appendix B.)

5.2.2.1 Parameter testing method. The acceptance criterion is calculated from the lot acceptance test data for a given PAR_{FAIL} value. For the case of testing at a single total-dose the lot acceptance criterion is:

$$DM(LOT) = \frac{PAR_{FAIL}}{e^{\overline{\ln(PAR_{RAD})}}} \geq e^{K_{TL} s_{\ln(PAR_{RAD})}}$$

for increasing parameter values, and

$$DM(LOT) = \frac{e^{\overline{\ln(PAR_{RAD})}}}{PAR_{FAIL}} \geq e^{K_{TL} s_{\ln(PAR_{RAD})}}$$

for decreasing parameter values,

where:

$$\overline{\ln(PAR_{RAD})} = \frac{1}{n} \sum_{i=1}^{n} \ln\left(PAR_{RAD_i}\right) \qquad \text{eq 5.2.1}$$

and

$$s_{\ln(PAR_{RAD})} = \left\{ \frac{1}{(n-1)} \sum_{i=1}^{n} \left[\ln\left(PAR_{RAD_i}\right) - \overline{\ln\left(PAR_{RAD}\right)} \right]^2 \right\}^{1/2} \qquad \text{eq. 5.2.2}$$

for the lot acceptance test data. K_{TL} is taken from Appendix B, Table XV for the specified values of C, P_{DIST}, and n.

5.2.2.2 Total-dose-to-failure method. For the case of multiple total-dose-to-failure-testing, the criterion is:

$$TDM(LOT) = \frac{e^{\overline{\ln(D_{FAIL})}}}{D_{SPEC}} \geq e^{K_{TL} s_{\ln(D_{FAIL})}}$$

where

$$\overline{\ln(D_{FAIL})} = \frac{1}{n} \sum_{i=1}^{n} \ln\left(D_{FAIL_i}\right) \qquad \text{eq. 5.2.3}$$

and

$$s_{\ln(D_{FAIL})} = \left\{ \frac{1}{(n-1)} \sum_{i=1}^{n} \left[\ln\left(D_{FAIL_i}\right) - \overline{\ln\left(D_{FAIL}\right)} \right]^2 \right\}^{1/2} \qquad \text{eq. 5.2.4}$$

for the lot acceptance test data. Examples of the use of the above criteria for lot acceptance are contained in 50.3 of Appendix B.

An effort should be made to run the tests up to a total-dose value, which is sufficiently large so as to make all parts achieve a total-dose value, PAR_{FAIL}. However, there may be cases where this is not possible and where only a portion of the parts has failed. In such a case, if a sufficient number of parts have failed, then the fluences-to-failure of those parts can be used. If the test has been run up to ten times the specification total-dose value, D_{SPEC}, and less than five parts have failed, then the characterization should be done in terms of the values of the parameter PAR at the total-dose value, D_{SPEC}, instead of in terms of failure fluences.

5.2.3 <u>Hardness assurance testing.</u> HA testing consists of either lot acceptance testing for HCC-1M parts, or sample testing for HCC-2 parts. The majority of the lot acceptance testing is at a single total dose although, occasionally, total-dose-to-failure testing may be required. All HCC-2 sample testing is normally carried out at a single total dose. Both types of testing are in accordance with MIL-STD-883 or MIL-STD-750, method 1019 and then details provided in 4.1.

Lot acceptance testing consists of randomly selecting sample parts from a lot to be evaluated, radiation-testing the parts, analyzing the data, and accepting the entire remaining lot of parts if the test data meet the acceptance criterion (see 5.2.2). Otherwise, the lot is rejected.

Sample testing consists of randomly selecting a few samples from a parts procurement, radiation-testing the parts, and analyzing the data to ensure that there have been no significant changes in the radiation sensitivity of the part type since the design phase characterization tests. If significant changes are indicated, the part categorization must be re-evaluated.

5.2.4 <u>Hardness assurance data analysis.</u> When the testing-by-attributes method is used, the data is recorded at the specified total-dose value. The lot is accepted if the post radiation parameter data meets the specified acceptance criterion (see 5.2.1.).

When a testing-by-variables method is specified, the test is conducted either at a single total-dose or at multiple total-dose-to-failure levels. For a single total-dose test, data analysis consists of using the Radiation Induced Parameter Values PAR_{RAD} for calculating the Design Margin, DM(LOT) and

$$e^{K_{TL} s_{\ln(PAR_{RAD})}}$$

The lot is then either accepted or rejected using the criteria of 5.2.2.

For the case of testing at multiple dose levels, the PAR_{RAD} versus total-dose values are plotted on graph paper, along with a horizontal line representing the Parameter Failure Value PAR_{FAIL}. The total-dose values where PAR_{RAD}, for each part, intersects the PAR_{FAIL} line are called the Total-Dose Circuit Failure Values, D_{FAIL}. The D_{FAIL} values are used to calculate the Total-Dose Design Margin, TDM(Lot), and

$$e^{K_{TL} s_{\ln(D_{FAIL})}}$$

The lot is then either accepted or rejected using the criterion of 5.2.2. Appendix B shows several detailed examples of using data analysis for lot acceptance testing.

5.2.5 Combining data. In order to increase the effective sample size and achieve a better characterization of a given product line, it is desirable to combine the data from different tests, where practicable. The combined data may greatly increase the confidence that can be placed in the test results. When sufficient data have been accumulated for a particular part type, the part characteristics and categorization should be re-evaluated It may, for example, ther be possible to reclassify HCC-1M part types as HCC-2 or to eliminate the need for periodic sample testing of HCC-2 part types.

Before the data from different lot-acceptance tests can be combined, the data must represent the same part type, bias conditions, and radiation environment for each vendor being evaluated.

5.3 Piece part hardness assurance management. The primary piece part HA management function is to establish and monitor the HA requirements for the production, and maintenance phases of the program Management personnel must ensure that all necessary HA requirements are furnished to the HA production and maintenance functions so as to preclude th need for additional design activity on their part. In addition, any relevant HA experience developed during the production phase of the program should be documented and passed on to the maintenance function

5.3.1 Procurement procedure. Detailed procurement procedures are beyond the scope of this document. The following information is offered as limited guidance for the procurement of HCC-1 and HCC-2 parts, as defined in 5.1.5. Definitions of the procurement, inspection, and wafer lot are given in MIL-M-38510 and MIL-S-19500

5.3.1.1 Hardness critical category 1M parts Where practicable, all HCC-1M parts are procurred, using single-wafer lot-conformance testing Single-wafer lot testing consists of sample-testing dice from a single wafer, with the dies mounted in separate packages to facilitate testing If the sample devices pass the lot acceptance test, the single wafer lot is accepted future devices fabricated from the wafer are acceptable. If the sample devices fail the lot acceptance test, the wafer is rejected, and devices fabricated from the wafer are not acceptable

An exception to single-wafer lot testing would be the case of large-scale integrated circuits, where a wafer may consist of only a few devices (circuits) In this case, it may be necessary to evaluate a diffusion run of several wafers for lot acceptance testing.

Production lot or inspection lot control is acceptable only when the vendor is unwilling to supply the device in wafer lots or there is a severe cost restriction imposed by the system. In production or inspection lot acceptance testing, the entire lot of devices is accepted if the sample devices pass the acceptance test requirements, otherwise, the entire lot of devices is rejected The samples must be randomly selected from the production or inspection lots.

5.3.1.2 Hardness critical category 1H parts These are otherwise non-critical parts that are hardness dedicated and their only function is to protect the circuit from specific radiation responses. They are included in hardness critical category 1 for system HA configuration and parts control purposes only.

5.3.1.3 Hardness critical category 1S parts These are sole-source parts, that is, parts whose radiation characterization tests indicate that only one manufacturer can meet the radiation response requirements of the system. They are included in hardness critical category 1 for system HA parts control purposes only.

5.3.1.4 Hardness critical category 2 parts. Where practicable, hardness critical category 2 parts should be procured directly from the manufacturer, represent current production, and include the manufacturer's assurance that the procuring activity will be advised regarding process changes. As a precautionary measure, HCC-2 parts, where TDM is less than 100, should be checked in a radiation environment at least once each six months and also after known process changes (see 5.1.5.3).

5.3.1.5 Hardness non-critical parts (HNC). When TDM is greater than 100 the parts are considered non-critical (see 5.1.5).

5.3.2 Hardness assurance testing. All HA total-dose radiation testing is carried out in accordance with MIL-STD-883, method 1019 or MIL-STD-750, method 1019. The test agency which carries out radiation tests is an important consideration. It is best if the vendor could do the radiation tests because such an arrangement results in fast lot acceptability and lower overall costs. However, most vendors have no radiation testing capability. Therefore, the tests must be done by the user or by a third party who has such a capability. The details of who does the testing, and where, may vary considerably from one device to another, but the final decision on testing must be made by the procurement agency.

Timing of the radiation test may also be an important consideration. Tests should be conducted as early as possible in the program so that lot failures will be known early and not impact the system production schedule. Failure of a lot sample means rejection of the entire lot. Failure of a significant percentage of lots may require a decision by the procurement activity to reclassify the device as not acceptable.

Where possible, arrangements should be made with the parts vendor to obtain early package samples from the production line for radiation testing. This should be done immediately after dicing, with the remaining dice held in storage until the results of the radiation lot acceptance tests are known. Failed lots may then be diverted to non-radiation usage without extra cost to the project, replacement lots may then be started through the line.

To ensure the integrity of the HA program, the procuring activity needs to define a vendor and radiation test-surveillance procedure.

5.3.3 Hardness assurance costs. The guidelines set forth in this document are intended to maximize the level of HA attained for the funds expended. When HA costs are considered, the overall design production and maintenance interrelationship must also be considered. Every effort must be made to minimize the very expensive lot acceptance testing For example, the additional cost of using a radiation hard part or special circuit design may be well justified if its use precludes future lot acceptance testing. Each part type, vendor selection, circuit design, and applications must be evaluated regarding the effect it has on the cost of the production and maintenance phase of the program.

5.3.4 Documentation. In addition to the normal HA documentation, it is important to include additional documentation for the vendor wafer-lot sampling procedures and for the radiation testing. The documentation should be sufficient to ensure the vendor's compliance with the wafer-lot sampling procedure and to maintain a permanent record of the program's history. Radiation-testing documentation should be sufficient to ensure that the test agency is in complete compliance with the system test requirements. In addition, it will be necessary to provide the details for each device type for the requirements of MIL-STD-883 and MIL-STD-750, method 1019, steady state total-dose irradiation procedure.

Custodians:
Army - ER
Navy - EC
Air Force - 17
NASA - NA

Review activities:
Army - AR, MI
Navy - SH
Air Force - 11, 19, 85, 99
DLA - ES
DNA - DS

User activities:
Army - SM
Navy - AS, CG, MC, OS

Agent:
DLA - ES

Preparing activity:
Navy - EC

(Project 59GP-0043)

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APPENDIX A

ELECTRONIC DEVICE CHARACTERISTICS IN AN IONIZING RADIATION ENVIRONMENT

10. GENERAL

10.1 Scope. This appendix details the more important parametric variables, typical values of hardness, and related data listed by generic class in an ionizing radiation environment at room temperature.

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. SPECIFIC SEMICONDUCTOR DEVICE RESPONSE

50.1 Bipolar transistors.

50.1.1 Introduction. Decrease in current gain and increase in leakage current are the most serious problems encountered in an ionizing radiation environment. The loss in gain is least at the current level of maximized gain and is most severe at low current levels. Table I summarizies the sensitive parameters of bipolar transistors.

TABLE I. Summary of radiation-sensitive parameters bipolar transistors

Parameter	MIL-STD-750 Method	Symbol	Parameter change
Forward current transistor ratio	3076.1	h_{FE}	Decreases
Collector to base cutoff current	3036.1	I_{CBO}	Increases
Collector to emitter cutoff current	3041.1	I_{CEO}	Increases
Saturation voltage	3071	$V_{CE(sat)}$	Increases
Noise voltage and current	3246.1	---	Increases

The changes described depend on the device type, manufacturer, date of production of the devices, and the bias condition during irradiation. Any of these variables can be the most important factor in any one case. The main factors which control the changes in the electrical properties of bipolar transistors for the long-term ionization effect are the buildup of trapped positive charge in the oxide near the silicon surface and creation of surface states at the silicon-silicon dioxide interface. The manufacturer's processing steps and resultant oxide quality have therefore a major impact on the resultant radiation hardness. This is why such wide variations in radiation hardness exist between the products of two manufacturers supplying the same part type. Even within a manufacturer's own product over a significant length of time, there can be large differences in radiation hardness. Within a given date code lot, there is also significant variation in the radiation response, which obeys a log normal distribution (reference A-1).

The following steps should be taken in selection of radiation-resistant device types and suitable operating conditions (reference A-2):

a. Give preference to silicon passivated devices, since they appear to be less sensitive to ionizing radiation surface effects.
b. Select devices with high cutoff frequencies.
c. Select transistors with low breakdown voltages.
d. Give preference to epitaxial construction, if available, for the particular application.
e. Provide ample base drive for transistors design to operate in saturation.

50.1.2 Gain.

50.1.2.1 Dependence on collector current. Bipolar transistors degrade in an ionizing radiation environment by an increase in the base current at a fixed collector current, I_C. It can readily be shown that the radiation-induced excess base current is proportional to the change in reciprocal dc gain, h_{FE}, which is denoted by $\Delta(1/h_{FE})$. Figure 5 gives the mean value of $\Delta(1/h_{FE})$ for different device types, after exposure to 125 krad(Si), as a function of the collector current. The decrease in damage rate with increasing collector current is apparent in all devices, $(1/h_{FE})$ varies approximately as $I_C^{-1/2}$. Most devices fall below the line $(1/h_{FE}) = 0.01\ I_C^{-1/2}$, where I_C is in mA, but a few devices exceed this line considerably. Figure 6 shows the variation in radiation response of 2N2222 transistors with collector current. The data is from two manufacturers, with one manufacturer's line quality shown over an extended period of time.

50.1.2.2 Dose. $\Delta(1/h_{FE})$ commonly shows a sublinear dependence on the total dose below 10^6 rad(Si) (see figure 7). However, the slope of the curves varies widely on different production lines with exponents in the range from 0.5 to 1. A superlinear dependence is sometimes seen. By 10^6 rad(Si), the ionizing radiation effects tend to saturate.

50.1.2.3 Bias conditions during irradiation. Bias conditions on devices during irradiation are one of the most important considerations for irradiated devices (reference A4 to A6). The following bias states are listed in increasing order of severity of radiation damage:

a. Both junctions forward biased.
b. Passive irradiation with all terminals shorted.
c. Collector-base junction reverse biased, base-emitter junction forward biased.
d. Collector-base junction reverse biased, base-emitter junction shorted.
e. Collector-base junction and base-emitter junctions both reverse biased.

The reduced dc gain that results from ionizing radiation is fairly stable at ambient temperatures, but the effect anneals out rapidly at elevated temperatures.

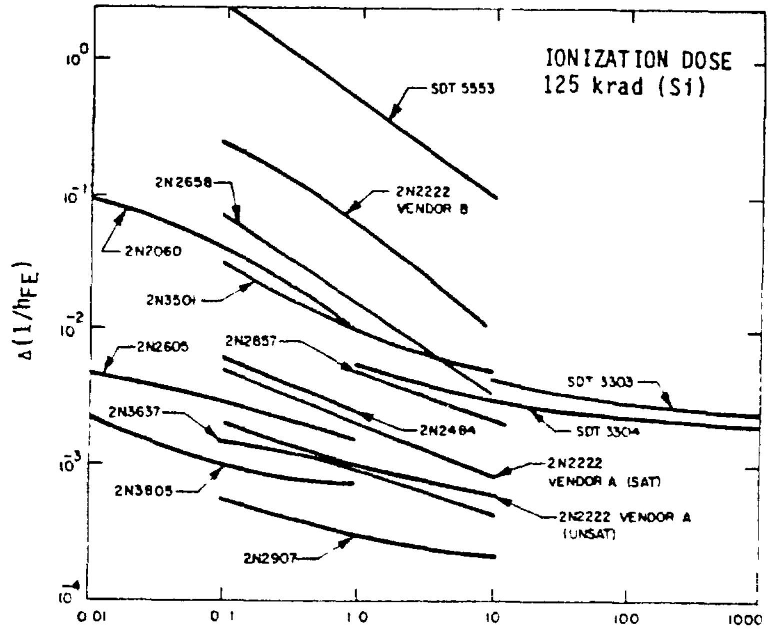


FIGURE 5. Mean $\Delta(1/h_{FE})$ vs I_C for different bipolar transistors (reference A-3).

50.1.2.4 Saturated and unsaturated operation. Although devices biased into saturation during radiation show the greatest radiation effects, devices irradiated under more severe radiation bias conditions may show a significant degradation in the unsaturated dc current gain. Experimental data has shown that the degradation in saturated current gain is either equal to or greater than the corresponding degradation in unsaturated current gain and that this degradation tends to increase the lower the collector voltage.

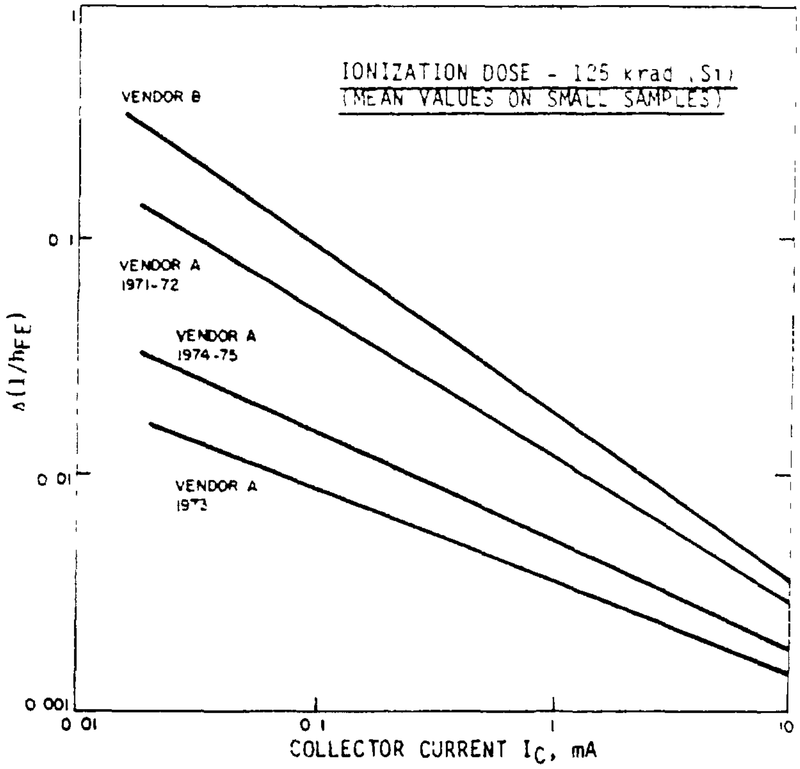


FIGURE 6. Typical ionization effects in 2N2222 bipolar transistors from two manufacturers (A and B), variation with time for manufacturer A.

50.1.2.5 High current gain. The degradation in dc gain is a minimum at the current level, I_C, where the pre-irradiation gain shows a peak. At still higher current levels, the radiation sensitivity increases. Wilson and Blair have shown that at high current levels the increase in base current required to keep the collector current constant during irradiation will lead to a widening of the effective base width by the Kirk Effect (reference A-7). The widening occurs when the injected minority charge density in the vicinity of the collector space-charge region becomes comparable to the fixed space-charge density found there. This occurs in typical silicon devices at current densities on the order of 1000 A/cm^2. The heavy concentration of minority carriers tends to increase the effective charge density in the space-Ocharge region next to the base and to decrease it next to the collector. This causes the space-charge region to shift toward the collector body, and thus the base is widened. The wider base causes a reduction in current gain.

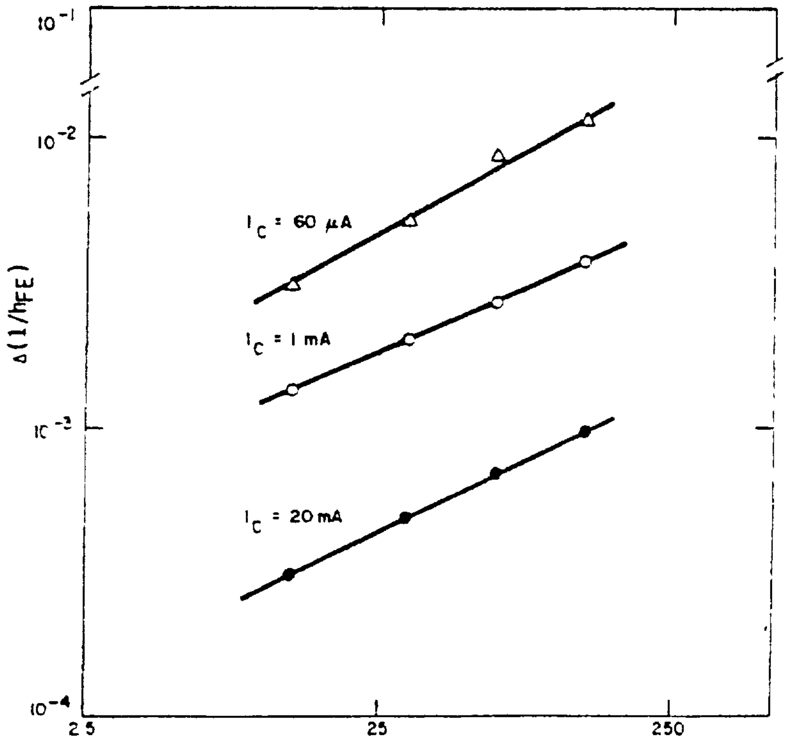


FIGURE 7. Log normal mean vs total dose for 2N2222 transistors operating in unsaturated mode at V_{CE} = 40 V at 3 collector current levels.

50.1.2.6 RF gain. Changes in RF gain are considerably less than the corresponding changes in dc gain. The current level of RF devices is normally chosen to optimize the power gain. This level usually produces minimum radiation damage and maximum annealing. Moreover, the structure of high-frequency devices minimizes the effect of damage.

50.1.3 Leakage currents. Surface ionization produces leakage currents in all semiconductor devices, which may vary by eight orders of magnitude depending on the device structure, surface conditions, and bias voltages. Leakage currents in excess of 10 mA can result in total destruction of the device. This may be avoided by the use of passivated silicon surfaces and low bias voltages. Leakage currents generated in passivated silicon surfaces are very dependent on the impurities introduced into the silicon oxide layer during manufacture.

50.1.3.1 Anneal. Leakage currents decay rather rapidly after removal from the radiation field. For this reason, leakage current measurements may need to be made immediately after the irradiation to simulate the radiation source. The leakage current anneals in the absence of radiation and more rapidly after removal of the bias voltage (see figure 8, reference A-8). When the bias voltage is restored, the leakage current will return asymptotically to its former value (memory effect). Passage of forward current across the junction will restore the leakage current to within one order of magnitude of its original value.

50.1.3.2 Saturation. At a fixed flux rate, the leakage current produced under a given bias condition will saturate after some period of time and will ultimately decrease. The saturation level and the time required to reach saturation depend on many parameters, including the condition of the oxide, the bias voltage, the dose rate, and the temperature.

50.1.3.3 I_{CBO}, I_{CEO}, I_{EBO}. Although the radiation-induced leakage current degradation is often shown as I_{CBO}, the degradation on I_{CEO} is even greater, since this is equal to I_{CBO} amplified by the current gain (reference A-9). On the other hand, the leakage current across the base-emitter junction is usually negligible. Figure 9 illustrates the relationship of the forward and reverse currents in an irradiated PNP transistor as a function of applied voltage.

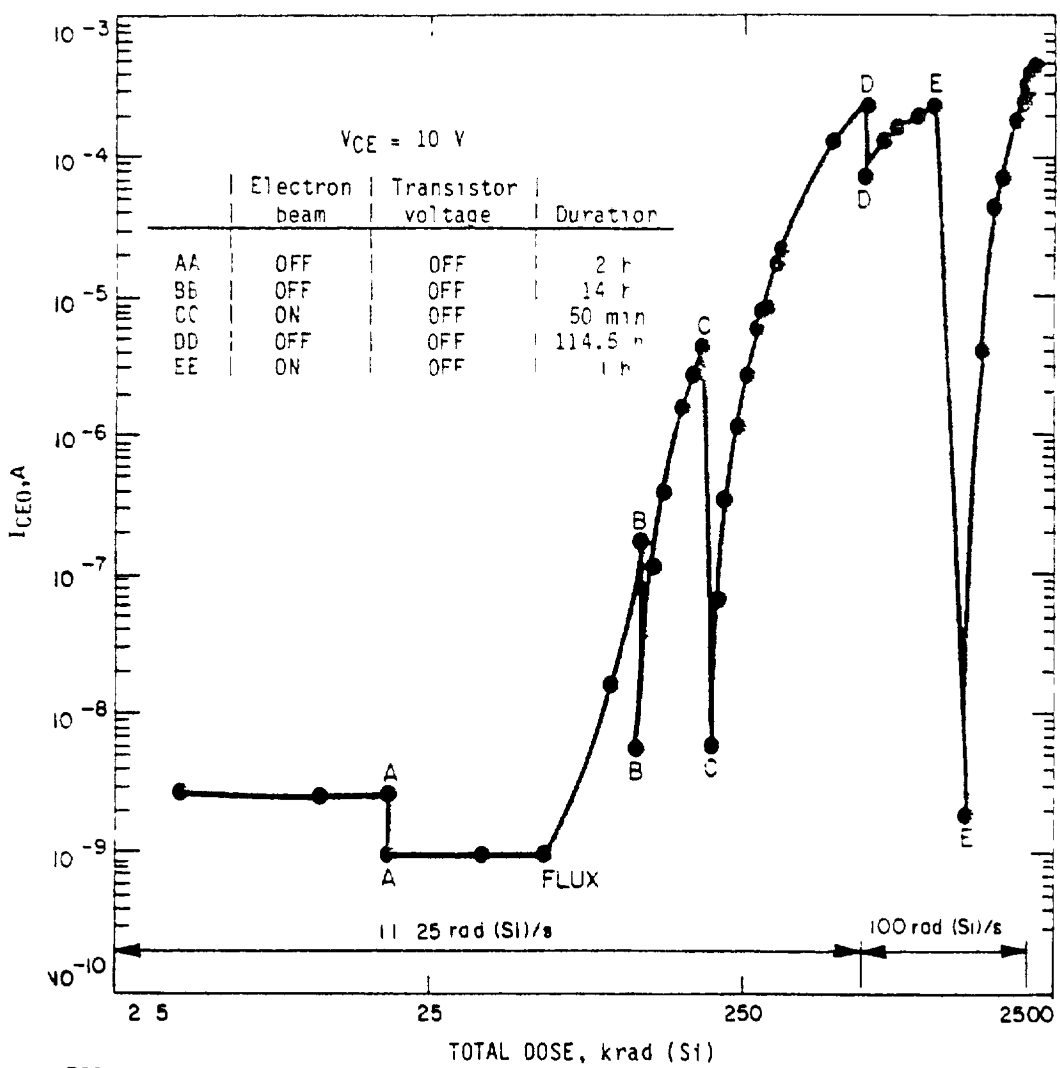


FIGURE 8. Annealing effects produced by time and irradiation without bias voltage. I_{CEO} vs total dose on an NPN planar transistor (reference A-8).

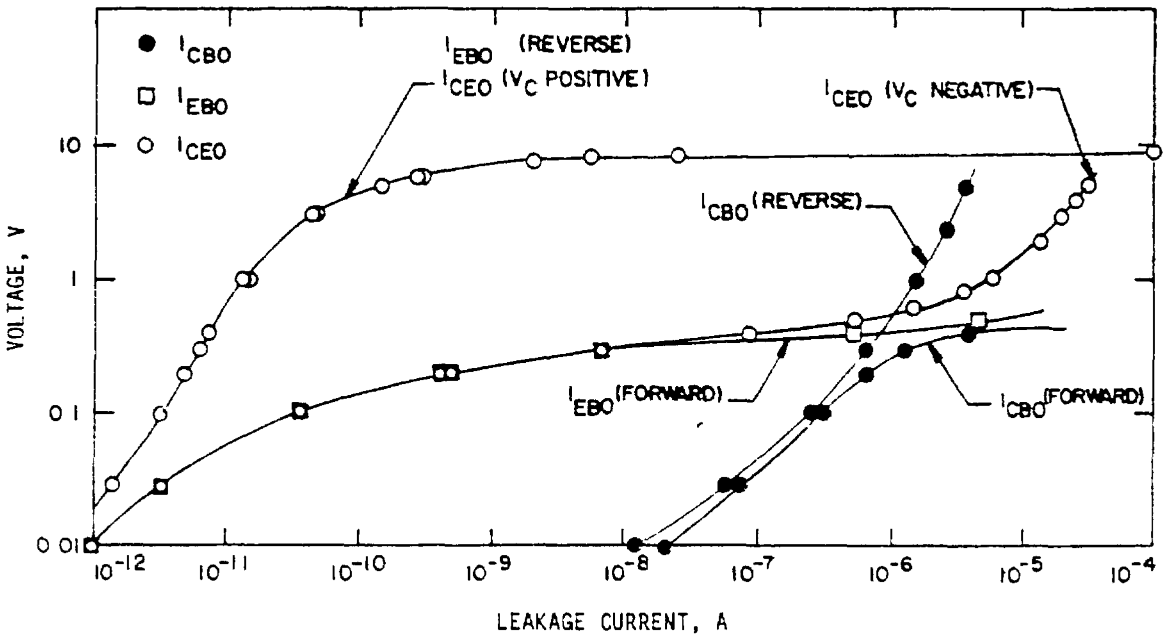


FIGURE 9. Leakage currents of an irradiated planar PNP transistor. Bias during irradiation: V_{CE} = -6 V, I_B = 0 at a total-dose = 5 Mrad(Si) (reference A-8).

50.1.4 Breakdown voltage. Radiation produces only slight changes in the breakdown voltage of a transistor whose breakdown voltage charcteristics before irradiation exhibit a sharp knee. There is a slight increase in the breakdown voltage accompanied by a softening of the knee, caused by the increased leakage current (figure 10). If the pre-irradiation breakdown characteristics are erratic or exhibit a rounded knee, the combined effect of radiation and the application of bias is unpredictable.

50.1.5 Second breakdown. At emitter-collector bias voltages above about 15 volts, ionizing radiation will produce large leakage currents in many planar transistors. These currents may ultimately cause the emitter and collector short-circuit due to second breakdown. This is a catastrophic failure of the transistor, which occurs when too much current is passed with the emitter-collector reverse-biased (reference A-10, A-11).

The threshold current for second breakdown is a function of the bias voltage - the greater the voltage, the lower the threshold. Radiation considerably lowers the threshold current at a given voltage (reference A-12, A-13). Second breakdown has been observed in a number of devices during irradiation. If not arrested in time, it may lead to a permanent short-circuit, since the heat generated cause the gold-germanium alloy under the silicon chip to melt and cover the glass insulation that separates the emitter terminal from the rest of the header. The two most important transistor design parameters with respect to second breakdown are the quality of the oxide and the geometry, which should be chosen to minimize the drift fields at a given applied potential.

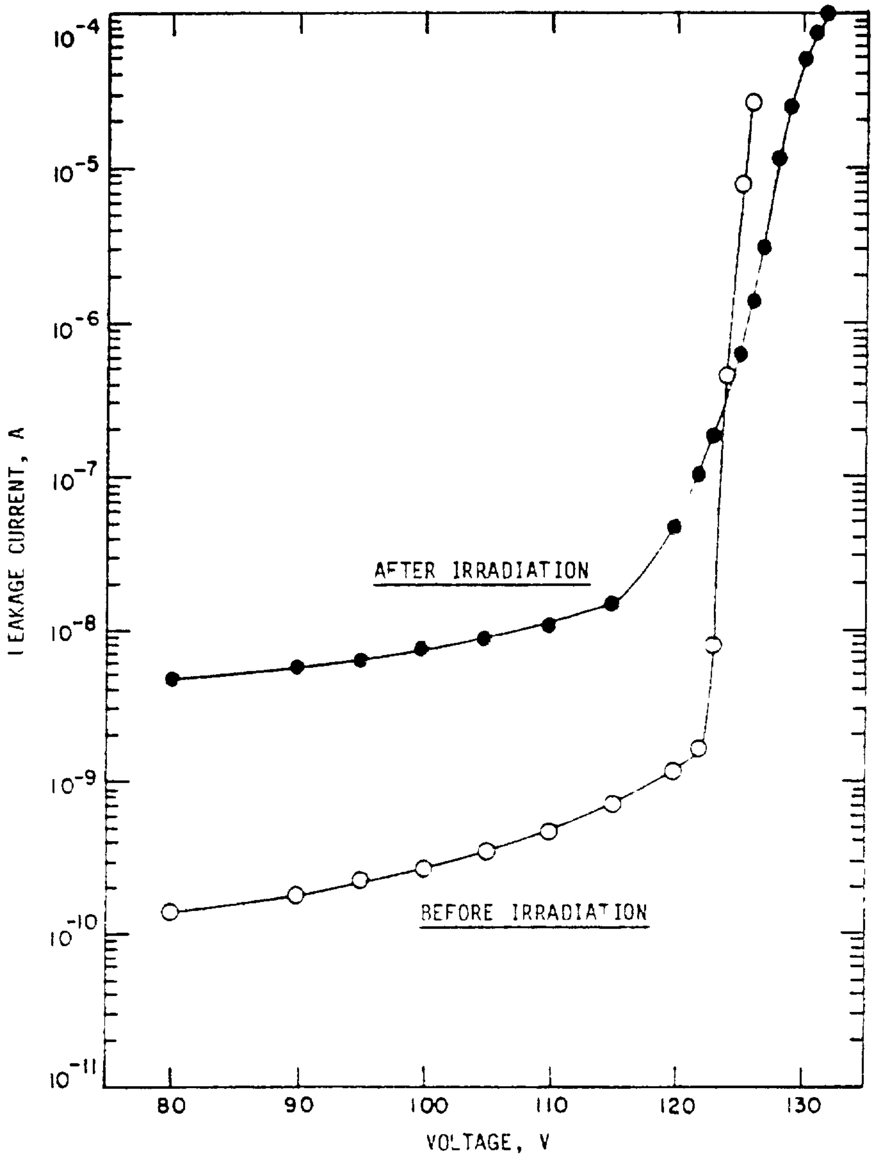


FIGURE 10. Collector-base breakdown voltage of a 2N1613 transistor. Bias during irradiation V_{CE} = 10 V, I_C = 5 mA at a total-dose = 2 5 Mrad(Si) (reference A-9)

After the transistor type has been chosen, the following guidelines may be useful in the selection of individual components and bias conditions:

a. Choose transistors with the lowest I_{CEO} at the operating bias voltage. Such units are least likely to reach the threshold for second breakdown.
b. Choose transistors with the lowest dc gain - the higher the gain, the higher the leakage current.
c. Reduce the base-emitter resistance to the lowest possible value. This not only reduces the collector leakage current under irradiation, but also raises the threshold for second breakdown.
d. Reduce the collector-emitter voltage to the lowest possible value.
e. Limit the collector current to the lowest possible value.

50.1.6 Collector-emitter saturation voltage. The collector-emitter saturation voltage, $V_{CE(sat)}$, is sensitive to ionizing radiation since it is a function of h_{FE}. When the transistor gain falls below the current gain of the test circuit, V_{CE} increases rapidly and will ultimately reach the supply voltage or breakdown voltage V_{CER}.

50.1.7 Base-emitter voltage. The base-emitter voltage, V_{BE}, is slightly affected by ionizing radiation.

50.1.8 Switching times. Ionizing radiation has only a slight effect on switching times. This effect depends on the parameters of the test circuit. There is a slight decrease in storage and fall time and an increase in rise time. The latter is caused by a drop in dc gain.

50.1.9 Noise. Both PNP and NPN transistors show an increase in noise voltage and noise current at dose levels above 10^4 rad(Si). PNP transistors generally degrade faster in noise at lower doses than NPN transistors (reference A-14). The noise increase levels off at approximately 10^6 - 10^7 rad(Si) for both types.

50.2 Junction gate field effect transistors. Junction-gate field effect transistors (JFET) have a considerably higher tolerance to radiation-induced bulk damage than bipolar transistors, since they are majority-carrier devices. However, n-channel devices with light doping in the gate region, are particularly susceptible to radiation-induced inversion effects. Such devices possess a relatively high gate breakdown voltage. In n-channel JFETs the positive space charge generated in the oxide induces an n-type inversion layer on the surface of the p-type gate region which generates leakage current upon back biasing the junction (reference A-8). On irradiation with the gate junction back biased, the gate current (I_{GS}) may increase sometimes well above 1 µA at 200 krad(Si), accompanied by similar changes in the drain current (I_{DS}). The gate leakage currents of most p-channel JFETs are less than 3 nA at 2.5 Mrad(Si).

The noise voltage at 10 Hz increases considerably in some irradiated devices, whereas the high-frequency noise figure increases only slightly. Low-frequency (1/f) noise is related to changes in the surface conditions, brought about by the irradiation which influences the 1/f noise (reference A-9). Since they are majority-carrier devices, field effect transistors have a considerably higher tolerance to bulk damage induced by electron irradiation than bipolar transistors. Table II summarizes the sensitive parameters of JFETs.

50.3 Linear integrated circuits. Most linear devices are used in the form of high-gain amplifiers, often in conjunction with very low input currents. Consequently, gain degradation and leakage effects affect their operation. CMOS linear devices are even more sensitive to ionizing radiation.

TABLE II. Summary of radiation-sensitive parameters, JFETs.

Parameters	MIL-STD-750 Method	Details at 25°C	Symbol	Parameter change
Gate to source leakage current	3411	V_{GS}, V_{DS} = 0 V	I_{GS}	Increases
Drain to source leakage current	3415	V_{DS}, V_{GS} = 0 V	I_{DS}	Increases

There is considerable information on radiation effects on operational amplifiers, comparators, voltage regulators, and analog switches. However, detailed information on total-dose irradiation is very limited for the following devices: voltage followers, current switches, A/D converters, D/A converters, sense amplifiers, phase-locked loop, voltage-controller oscillators, amplifiers, and mixers (reference A-15).

50.3.1 Operational amplifiers. Total-dose radiation data is available on the following three types of operational amplifiers: medium offset current operational amplifiers with input offset current greater than 1 nA; low offset current operational amplifiers with input offset currents less than 100 pA; and JFET input devices with input offset currents of less than 10 pA. These are the pre-irradiation values of input offset current. Table III summarizes the sensitive parameters of operational amplifiers.

TABLE III. Summary of radiation-sensitive parameters, operational amplifiers.

Parameter	MIL-STD-883 Method	Symbol	Parameter change
Offset voltage	4001	V_{OS}	a
Offset current	4001	I_{OS}	a
Input bias current	4001	I_B	Increases
Open loop gain	4004	A_{VOL}	Decreases
Output sink current	--	I_{Sink}	Decreases
Output source current	--	I_{Source}	Decreases

[a]The change may be positive or negative but the absolute Δ change increases.

50.3.1.1 Low input offset current operational amplifiers. Low input offset current operational amplifiers are extremely sensitive to ionizing radiation (reference A-16, A-17). Even at comparatively low fluences, there is a significant change in the dc parameters, causing them to exceed the specification limits. Also, at these radiation levels, some device types may exhibit failure modes that render the devices inoperative.

Table IV lists typical values for two types of low input offset current operational amplifiers, from three different manufacturers, when irradiated to 10^6 rad(Si).

TABLE IV. Low input offset current operational amplifiers irradiated to 10^6 rad(Si).

Manufacturer and device type	ΔV_{OS} (mV)	ΔI_{OS} (na)	ΔI_B (nA)	$+A_{VOL}$ (dB) 2 mA load	$-A_{VOL}$ (dB) 2 mA load
A	0.17	0.13	8.0	95	85
B	20	20	200	60	Fail
C	Fail	Fail	Fail	Fail	Fail

Some of these device types have been successfully hardened by several manufacturers. Yet, there is still a wide divergence of post-irradiation shifts in parametric values between wafer lots. Radiation quality conformance tests are required.

50.3.1.2 Medium input offset current operational amplifiers. The greatest number of operational amplifiers falls into this medium input offset current group. Table V lists typical values for three different operational amplifier types from three different manufacturers.

TABLE V. Medium input offset current operational amplifiers at various doses of radiation.

Manufacturer and device type	Total dose rad(Si)	ΔV_{OS} (mV)	ΔI_{OS} (nA)	ΔI_B (nA)	$+A_{VOL}$ (dB) 5 mA load	$-A_{VOL}$ (dB) 5 mA load
A	1×10^6	1.5	2.5	100	82	84
B	1.2×10^5	4.3	50	650	Fail	Fail
C[b]	1×10^6	0.88	44	52	102	109

[b]developed for military systems.

Some of the devices are severely degraded at 50 krad(Si). However, several manufacturers have hardened some of these device types. As for the low input offset current devices, there are wide divergencies of post-irradiation shifts in parametric values between wafer lots, and radiation quality-conformance tests are required. Also included in this group are the specially hardened operational amplifiers developed for military systems (reference A-18). These devices have small parameter degradation to 10^6 rad(Si).

50.3.1.3 FET input operational amplifiers. These devices use JFET inputs and consequently have very low (pA) initial input offset currents but degrade rapidly with radiation dose (reference A-8). Bias current on some devices increases 1000 times at 30 krad(Si), and most devices are catastrophic failures at 125 krad(Si).

50.3.2 Comparators. Total-dose radiation data is available on the following two types of comparators medium offset current comparators with input offset currents greater than 100 nA and low offset current comparators with input offset currents less than 100 nA. Table VI summarizes the sensitive parameters of comparators.

TABLE VI. Summary of radiation-sensitive parameters, comparators.

Parameter	MIL-STD-883 Method	Symbol	Parameter change
Offset voltage	4001	V_{OS}	c
Offset current	4001	I_{OS}	c
Input bias current	4001	I_B	Increases
Open loop gain	4004	A_{VOL}	Decreases
Output sink current	--	I_{Sink}	Decreases
Output source current	--	I_{Source}	Decreases

[c]The change may be positive or negative but, the absolute Δ change increases.

50.3.2.1 Medium offset current comparators. Comparators with medium input offset current, i.e., LM106 and LM710, remain within manufacturers specification at least up to 250 krad(Si).

50.3.2.2 Low offset current comparators. Comparators with low input offset current, i.e., LM111 and LM139, are sensitive to ionizing radiation. The LM111 experiences considerable increases in the dc parameters for most manufacturer's devices. However, several manufacturers have made devices hard to 10^6 rad(Si). The LM139 devices are extremely dependent on the bias conditions during irradiation. Several manufacturers produce an LM139 which remain within manufacturers specifications to 10^6 rad(Si) (reference A-16).

50.3.3 Voltage regulators. Voltage regulators are relatively unaffected by ionizing radiation. The line and load regulations of LM723 change by less than 0.03 percent at 125 krad(Si). The stability of the LM105 is even better (<0.015 percent change). The LM103 regulator diode is known to remain within manufacturers specification to 2.5 Mrad(Si).

50.3.4 Voltage followers. The LM102 voltage follower remains within manufacturers specification to at least 250 krad(Si).

50.3.5 Analog switches (references A-3).

50.3.5.1 Analog switches without MOS devices. Such devices usually consist of a driver circuit and JFET switching circuits. They are frequently of hybrid construction. Increased leakage in $I_{S(off)}$ is caused by an increase in gate leakage of JFET's under 30V gate bias. Leakage currents up to 25 nA are observed in the device types DG129 and DG133, and leakage currents up to 50 nA are measured in the DG141 when the devices are irradiated to 125 krad(Si). The worst-case bias condition during radiation is with the inputs in the off condition

50.3.5.2 Analog switches containing MOS devices Analog switches containing MOS devices are very sensitive to radiation, but the effects vary strongly with the bias condition during radiation, the bias conditions during measurement of the electrical parameters, and also with the manufacturer. Hardness of these devices is strongly dependent on the processing steps, which vary widely between manufacturers A dynamic test indicated that the DG161 device can latch up at about 125 krad(Si), producing $I_{S(off)}$ and $I_{D(off)}$ currents up to 1 mA The DGM111 and the DG125 showed increases up to 5.5 kΩ in $r_{DS(on)}$ at 125 krad(Si), but this parameter is very dependent on bias conditions (reference A-15)

50.3.6 Current switches. The allowable error in the current switches is usually expressed in terms of fractions of the least significant bit (LSB), with normal allowable errors being of the order of 1/2 LSB. The LSB error is due to a decrease in the LSB output current. A radiation-induced leakage path produces a loss in collector current, which causes the device to be completely inoperative at 250 krad(Si) as the LSB current drops to zero. No problems have been observed in current gain, logic threshold, output leakage current, or response time.

50.3.7 A/D converter. Most A/D converters are sensitive to an ionizing irradiation environment. CMOS devices are very sensitive while bipolar devices are significantly harder. Table VII lists the A/D converters recently tested and their reported hardness

TABLE VII. Summary of A/D converters.

Resolution (bits)	Technology	Reported hardness
4	bipolar	300 krad(Si)
8	bipolar	75 krad(Si)[d]
10	I^2L	75 krad(Si)[d]
10	CMOS	3 krad(Si)
10	CMOS	6 krad(Si)
12	I^2L hybrid	30 krad(Si)[d]
12	hybrid	10 krad(Si)[d]
12	hybrid	75 krad(Si)[d]

[d]Some parameters out of manufacturers specification.

50.3.8 D/A converter. Most D/A converters are sensitive to an ionizing irradiation environment. Table VIII lists the D/A converters recently tested and their reported hardness.

TABLE VIII. Summary of D/A converters.

Resolution (bits)	Technology	Reported hardness
8	bipolar	75 krad(Si)
8	bipolar	75 krad(Si)[e]
8	bipolar	75 krad(Si)[e]
10	CMOS	10 krad(Si)
12	CMOS	10 krad(Si)
12	bipolar	15 krad(Si)

[e]Some parameters out of manufacturers specification.

50.3.9 Sense amplifier. In a sense amplifier, radiation produced a decrease in the spontaneous switching time. The propagation delay increased slightly at 60 krad(Si) but reverted close to its pre-irradiation level at 125 krad(Si). There was no significant change in any other parameter.

50.3.10 Phase-locked loop. There is a large variation in sensitivity to total dose effects in phase-locked loop devices. Some devices show significant degradation at 20 krad(Si), while other devices show little degradation at 250 krad(Si).

50.3.11 Voltage-controlled oscillator. A voltage-controlled oscillator has been irradiated to 125 krad(Si) with a less than 1.0% decrease in frequency and no measurable change in the output voltage.

50.3.12 RF amplifiers. RF amplifiers which have been irradiated indicate no measurable positive gain change and only a moderate negative change. Worst-case gain change amounted to +1.0 dB at a total dose of 250 krad(Si).

50.3.13 RF mixers. RF mixers which have been irradiated indicate no significant difference after being irradiated to 250 krad(Si).

50.4 Bipolar digital integrated circuits. In most cases, with the exception of devices made with new advanced oxide isolation techniques (e.g., IMOX, FAST, AS, ALS), the radiation effects at 10^6 rad(Si) will be negligible. At the highest radiation levels fan-out or output drive capability is reduced. Table IX summarizes the sensitive parameters of bipolar digital devices.

TABLE IX. Summary of radiation-sensitive parameters, bipolar digital devices.

Parameter	MIL-STD-883 Method	Symbol	Parameter change
Output drive (fan-out)	3011.1	--	Decreases

At the time of this writing, it is too early to determine the radiation hardness of devices made with new advanced oxide isolation techniques though these devices are known to be much softer than devices made with older techniques.

50.5 MOS devices. MOS devices are very sensitive to total ionization doses. The main effect is a shift in the gate threshold voltage, $V_{GS(th)}$, toward more negative values. Secondary effects are a decrease in the transconductance and an increase in the source and drain-leakage currents. For a PMOS switch, these effects shift the switching voltage to a more negative value and decrease the output voltage, V_{OUT}. Commercial MOS devices may exhibit significant degradation for doses of 10^4 rad(Si).

The gate voltage shift can be reduced by holding the MOS body (substrate) at the most positive potential. The effect of a given threshold shift may be tolerable if the gate voltage is more negative than the degraded threshold voltage.

In general, the output voltage is used to drive other logic gates. The threshold voltages of these logic gates will also have experienced a negative shift. The combined output/gate degradation can be offset by operating at a more negative drain/gate potential on the load device. Figure 11 suggests several hardening techniques for MOS devices.

Typical propagation time (t_p) increase is 35% for both EH4600 Series and CD400 Series CMOS (reference A-3). Some outliers increased as much as 10 times the mean increase after irradiation to 150 krad(Si). Typical quiescent supply current (I_{SS}) increased 25 to 10,000 times its initial value after irradiation to 150 krad(Si). Several manufacturers are producing special radiation-hardened CMOS devices hard to 10^6 rad(Si). Table X summarizes the sensitive parameters of MOS devices.

50.6 LSI. All commercially available microprocessors, memories, and other circuits built with MOS technology are very sensitive to an ionizing radiation environment. The failure level depends on the technology as shown in table XI. Bipolar devices are somewhat harder. A list of different processing techniques potentially available for the fabrication of LSI devices is given in table XI.

Most MOS memories will fail within the range of 10^3 to $2x10^4$ rad(Si) (reference A-21). Although some NMOS memories have been reported to be hard to 10^5 rad(Si), in general, silicon gate dynamic NMOS memories are very radiation soft. Magnetic bubble memories are extremely radiation hard. Bipolar PROM's are relatively hard.

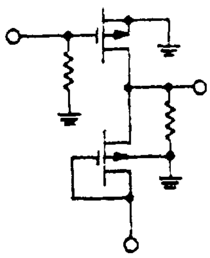
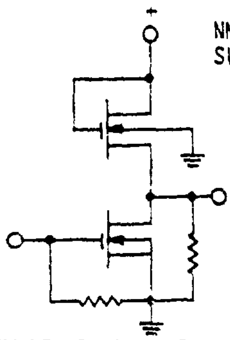
Typical circuit	Radiation response	Hardening techniques
 PMOS SWITCH	Negative threshold voltage shift Less output voltage Increased voltage drop across load	Increase gate voltage Use more positive potential for body gate
 NMOS SWITCH	Negative threshold voltage shift Switch will not turn off More output voltage Increased voltage drop across load Increase power consumption	Use PMOS Increase gate voltage Use more positive potential for body gate Use negative input bias

FIGURE 11. Suggested total-dose hardening techniques for MOS devices (reference A-19)

TABLE X. Summary of radiation-sensitive parameters, MOS devices.

Parameter	MIL-STD-750 Method	Symbol	Parameter change
Gate threshold voltage	3001.1	$V_{GS(th)}$	More negative
Output voltage	3006.1	V_{OUT}	Decreases
Propagation delay	3004.1	t_p	Increases
Source supply	3005.1	I_{SS}	Increases

50.7 Diodes and rectifiers. Total-dose effects in switching and rectifying diodes appear as a change in the forward voltage (V_F), leakage current (I_R), and the breakdown voltage (V_B). Parameter changes are not linear with cumulative dose. In general, the parameter changes are barely detectable at 10 krad(Si). At 100 krad(Si), the usual parameters of design importance, ΔV_F and ΔI_R, are less than 50 mV and 10 μA, respectively.

50.7.1 Zener and reference diodes. It is possible to determine the radiation-induced change in the zener voltage to an accuracy of ±1 mV by relatively simple means. The absolute value of the zener voltage, which is a strong function of the zener current, has been determined easily to an accuracy of about ±10 mV (reference A-2). With zener and reference diodes, the zener reference voltage (Vz) usually changes less than 0.03 percent at 100 krad(Si), thus ΔVz is the key design parameter. For reference diodes, the ΔVz should change less than 0.1 percent at 10 krad(Si). Precision applications often require much greater accuracy, and under these conditions the determination of any total dose radiation effects presents a measurement problem.

Some zener and reference diodes have shown significant leakage currents at 250 krad(Si). High voltage zener devices (over 70 volts) shift 20 mV at a fluence of 250 krad(Si). In general, zener and reference diodes are radiation sensitive in very high precision applications only.

50.7.2 Constant-current diodes. These devices are considered insensitive to radiation damage to 250 krad(Si).

50.7.3 Other diodes and rectifiers. These devices are considered insensitive to radiation damage to 250 krad(Si), although some devices have significant leakage currents at 250 krad(Si).

TABLE XI. LSI technology (reference A-20).

Process	Reported hardness
n-MOS	10^3 x 10^4 rad(Si)
p-MOS	5 x 10^4 rad(Si)
Unhardened CMOS	10^3 - 10^4 rad(Si)
Hardened bulk MOS, metal gate	10^6 rad(Si)
Hardened CMOS-SOS, metal gate	5 x 10^5 rad(Si)
Bipolar TTL, ECL*	10^6 rad(Si)
I^2L*	10^5 - 10^6 rad(Si)

* See the exceptions for devices made with new oxide isolation techniques as noted in paragraphs 5 1.1.2 and 50.4

50.7.4 Silicon-controlled rectifiers. Radiation-induced surface ionization will lower the level of the switching point by generating a leakage current across the reverse-biased center junction in a silicon-controlled rectifier (SCR) This in turn will raise all the currents through the device in the off-condition If the leakage current rises above a certain threshold value, the SCR is permanently turned on (reference A-9). In SCRs, gate voltage is decreased moderately and gate current is increased moderately by a total dose of 250 krad(Si).

50.8 Optical devices. All types of optical devices are very sensitive to radiation-induced damage The light sources are more sensitive to radiation damage than the light detectors. Table XII summarizes the sensitive parameters of optical devices.

TABLE XII. Summary of radiation-sensitive parameters, optical devices.

GaAs LEDs	Decreased output
Si photodetectors	Decreased sensitivity Increased dark current
Optical isolators	Decreased coupling

50.8.1 GaAs LEDs. The emission efficiency of GaAs LEDs is greatly reduced by irradiation, and some devices degrade more than others. Most GaAs LEDs incur reduced light intensity by 30% at 250 krad(Si). Epitaxial GaAs LEDs incur reduced light intensity by 90% at 250 krad(Si). See reference A-22 for additional information.

50.8.2 Silicon photodetectors. Silicon photodetectors are very sensitive to irradiation. The radiation effects depend on the temperature of the device as well as the energy of the electron and its fluence.

50.8.3 Photomultipliers. Photomultipliers appear to have no permanent damage due to displacement or ionization but are very susceptible to dose-rate effects due to scintillation in the glass envelopes and in the phosphor.

50.8.4 Solar cells. Standard n on p solar cells are relatively insensitive to ionization radiation to 2.5 Mrad(Si). For additional information see reference A-23.

50.8.5 Optical isolators. Optical isolators are a combination of a GaAs LED and either a photodiode or phototransistor. The isolators containing phototransistors are more sensitive to irradiation than those containing photodiodes. In general, optical isolators are within manufacturer's specification to 10^6 rad(Si).

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APPENDIX B

EXAMPLES OF DATA ANALYSIS

10. GENERAL

10.1 Scope. This appendix provides detailed examples of determining the DMBP value (see 5.1.5.2.1), categorizing part types (see 5.1.5.2.2) and lot acceptance testing (see 5.2).

20. REFERENCE DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. DETAILED EXAMPLES

50.1 Determining the DMBP value. A DMBP value, corresponding to a given cumulative proportion of the distribution, P_{DIST} (part survival probability), may be determined for moderate total-dose requirements as in the following example

$$DMBP = e^{K(P_{DIST}) s_{ln} (Max)}$$

where $K(P_{DIST})$ is at the P_{DIST} fractile of a standard normal distribution, and $s_{ln}(Max)$ is an estimate of the largest expected standard deviation that would result from characterization tests.

Example. In this hypothetical example, we will assume the log normal distribution, a P_{DIST} value of 4.417 (99.9995 survival probability), and an $s_{ln}(Max)$ of 0.531.

$$\text{Since } K\ (0.999995) = 4.417$$

$$DMBP = e^{4.417 \times 0.531} \quad 10$$

The assumptions used for determining the DMBP value will depend on the individual system requirements. However, in assuming a value for $s_{ln}(Max)$, the application should be limited to systems that have moderate total-dose radiation requirements (see 5.1.2.1). The reason is that DMBP requires very high design margins, which might not be met in systems with stringent requirements. Otherwise the PCC method of categorizing parts, as discussed in 5.1.5.2.2, should be considered.

50.2 Categorizing part types. Three example will be given to illustrate how a part type may be categorized on the basis of characterization data. Two of the examples are based on using the D_{FAIL} values. The third example is for the special case where there are less than three D_{FAIL} values available (see 5.1.3.2). In this case it is necessary to use the PAR_{RAD} values. Although a minimum of ten test samples is normally recommended, only five parts are used in order to simplify the following examples:

EXAMPLE 1. Categorization of the LM108 operational amplifier on the basis of input bias current, I_B, for a test sample of five parts using D_{FAIL} values.

APPENDIX B

TABLE XIII. K_{TL} factors for one-sided tolerance limits for normal distributions.

	C = 0.75					C = 0.90				
n \ P	0.75	0.90	0.95	0.99	0.999	0.75	0.90	0.95	0.99	0.999
3	1.464	2.501	3.152	4.396	5.805	2.602	4.258	5.310	7.340	9.651
4	1.256	2.134	2.680	3.726	4.910	1.972	3.187	3.957	5.437	7.128
5	1.152	1.961	2.463	3.421	4.507	1.698	2.742	3.400	4.666	6.112
6	1.087	1.860	2.336	3.243	4.273	1.540	2.494	3.091	4.242	5.556
7	1.043	1.791	2.250	3.126	4.118	1.435	2.333	2.894	3.972	5.201
8	1.010	1.740	2.190	3.042	4.008	1.360	2.219	2.755	3.783	4.955
9	0.984	1.702	2.141	2.977	3.924	1.302	2.133	2.649	3.641	4.772
10	0.964	1.671	2.103	2.927	3.858	1.257	2.065	2.568	3.532	4.629
11	0.947	1.646	2.073	2.885	3.804	1.219	2.012	2.503	3.444	4.515
12	0.933	1.624	2.048	2.851	3.760	1.188	1.966	2.448	3.371	4.420
13	0.919	1.606	2.026	2.822	3.722	1.162	1.928	2.403	3.310	4.341
14	0.909	1.591	2.007	2.796	3.690	1.139	1.895	2.363	3.257	4.274
15	0.899	1.577	1.991	2.776	3.661	1.119	1.866	2.329	3.212	4.215
16	0.891	1.566	1.977	2.756	3.637	1.101	1.842	2.299	3.172	4.164
17	0.883	1.554	1.964	2.739	3.615	1.085	1.820	2.272	3.136	4.118
18	0.876	1.544	1.951	2.723	3.595	1.071	1.800	2.249	3.106	4.078
19	0.870	1.536	1.942	2.710	3.577	1.058	1.781	2.228	3.078	4.041
20	0.865	1.528	1.933	2.697	3.561	1.046	1.765	2.208	3.052	4.009
21	0.859	1.520	1.923	2.686	3.545	1.035	1.750	2.190	3.028	3.979
22	0.854	1.514	1.916	2.675	3.532	1.025	1.736	2.174	3.007	3.952
23	0.849	1.508	1.907	2.665	3.520	1.016	1.724	2.159	2.987	3.927
24	0.845	1.502	1.901	2.656	3.509	1.007	1.712	2.145	2.969	3.904
25	0.842	1.496	1.895	2.647	3.497	0.999	1.702	2.132	2.952	3.882
30	0.825	1.475	1.869	2.613	3.454	0.966	1.657	2.080	2.884	3.794
35	0.812	1.458	1.849	2.588	3.421	0.942	1.623	2.041	2.833	3.730
40	0.803	1.445	1.834	2.568	3.395	0.923	1.598	2.010	2.793	3.679
45	0.795	1.435	1.821	2.552	3.375	0.908	1.577	1.986	2.762	3.638
50	0.788	1.426	1.811	2.538	3.358	0.894	1.560	1.965	2.735	3.604

TABLE XIII. K_{TL} factors for one-sided tolerance limits for normal distributions - Continued.

	C = 0.95					C = 0.99				
n \ P	0.75	0.90	0.95	0.99	0.999	0.75	0.90	0.95	0.99	0.999
3	3.804	6.158	7.655	10.552	13.857	---	---	---	---	---
4	2.619	4.163	5.145	7.042	9.215	---	---	---	---	---
5	2.149	3.407	4.202	5.741	7.501	---	---	---	---	---
6	1.895	3.006	3.707	5.062	6.612	2.849	4.408	5.409	7.334	9.550
7	1.732	2.755	3.399	4.641	6.061	2.490	3.856	4.730	6.411	8.348
8	1.617	2.582	3.188	4.353	5.686	2.252	3.496	4.287	5.811	7.566
9	1.532	2.454	3.031	4.143	5.414	2.085	3.242	3.971	5.389	7.014
10	1.465	2.355	2.911	3.981	5.203	1.954	3.048	3.739	5.075	6.603
11	1.411	2.275	3.815	3.852	5.036	1.854	2.897	3.557	4.828	6.284
12	1.366	2.210	2.736	3.747	4.900	1.771	2.773	3.410	4.633	6.032
13	1.329	2.155	2.670	3.659	4.787	1.702	2.677	3.290	4.472	5.826
14	1.296	2.108	2.614	3.585	4.690	1.645	2.592	3.189	4.336	5.651
15	1.268	2.068	2.566	3.520	4.607	1.596	2.521	3.102	4.224	5.507
16	1.242	2.032	2.523	3.463	4.534	1.553	2.458	3.028	4.124	5.374
17	1.220	2.001	2.486	3.415	4.471	1.514	2.405	2.962	4.038	5.268
18	1.200	1.974	2.453	3.370	4.415	1.481	2.357	2.906	3.961	5.167
19	1.183	1.949	2.423	3.331	4.364	1.450	2.315	2.855	3.893	5.078
20	1.167	1.926	2.396	3.295	4.319	1.424	2.275	2.807	3.832	5.003
21	1.152	1.905	2.371	3.262	4.276	1.397	2.241	2.768	3.776	4.932
22	1.138	1.887	2.350	3.233	4.238	1.376	2.208	2.729	3.727	4.866
23	1.126	1.869	2.329	3.206	4.204	1.355	2.179	2.693	3.680	4.806
24	1.114	1.853	2.309	3.181	4.171	1.336	2.154	2.663	3.638	4.755
25	1.103	1.838	2.292	3.158	4.143	1.319	2.129	2.632	3.601	4.706
30	1.059	1.778	2.220	3.064	4.022	1.249	2.029	2.516	3.446	4.508
35	1.025	1.732	2.166	2.994	3.934	1.195	1.957	2.431	3.334	4.364
40	0.999	1.697	2.126	2.941	3.866	1.154	1.902	2.365	3.250	4.255
45	0.978	1.669	2.092	2.897	3.811	1.122	1.857	2.313	3.191	4.168
50	0.961	1.646	2.065	2.863	3.766	1.096	1.821	2.269	3.124	4.096

Let us consider the radiation-induced change in input bias current, ΔI_B, data. The system in this example has the following requirements:

$$D_{SPEC} = 150 \text{ krad(Si)}$$

$n = 5$, C is 90% and P_{DIST} is 99.9% for determining PCC.

The worst case circuit failure limit, PAR_{FAIL}, for ΔI_B is 10 nA. We then proceed as follows:

Step 1 - Irradiate the test samples in accordance with the requirements of paragraph 4.1 at increasing dose levels until all of the parts have reached the PAR_{FAIL} value of 10 nA. Plot ΔI_B versus total dose as shown on figure 12 for each part.

Step 2 - Determine the total-dose circuit-failure value, D_{FAIL}, for each part at the PAR_{FAIL} value of 10 nA from figure 12.

Test part	D_{FAIL} in krad(Si)
1	650
2	800
3	500
4	420
5	350

Step 3 - Determine $TDM = D_{MF}/D_{SPEC}$ and $s_{\ln(D_{FAIL})}$ using the D_{FAIL} values from Step 2.

From eq. 5.1.1,

$$D_{MF} = e^{\overline{\ln(D_{FAIL})}} = 521 \text{ krad(Si)}$$

and

$$D_{SPEC} = 150 \text{ krad(Si)}$$

Therefore

$$TDM = \frac{D_{MF}}{D_{SPEC}} = \frac{521}{150} = 3.5$$

From eq. 5.1.2,

$$s_{\ln(D_{FAIL})} = \left\{ \frac{1}{(n-1)} \sum_{i=1}^{n} \left[\ln\left(D_{FAIL_i}\right) - \overline{\ln\left(D_{FAIL}\right)} \right]^2 \right\}^{1/2}$$

$$= 0.331$$

Step 4 - Determine PCC using the value of $s_{\ln(D_{FAIL})} = 0.331$ from Step 3, and figure 12.

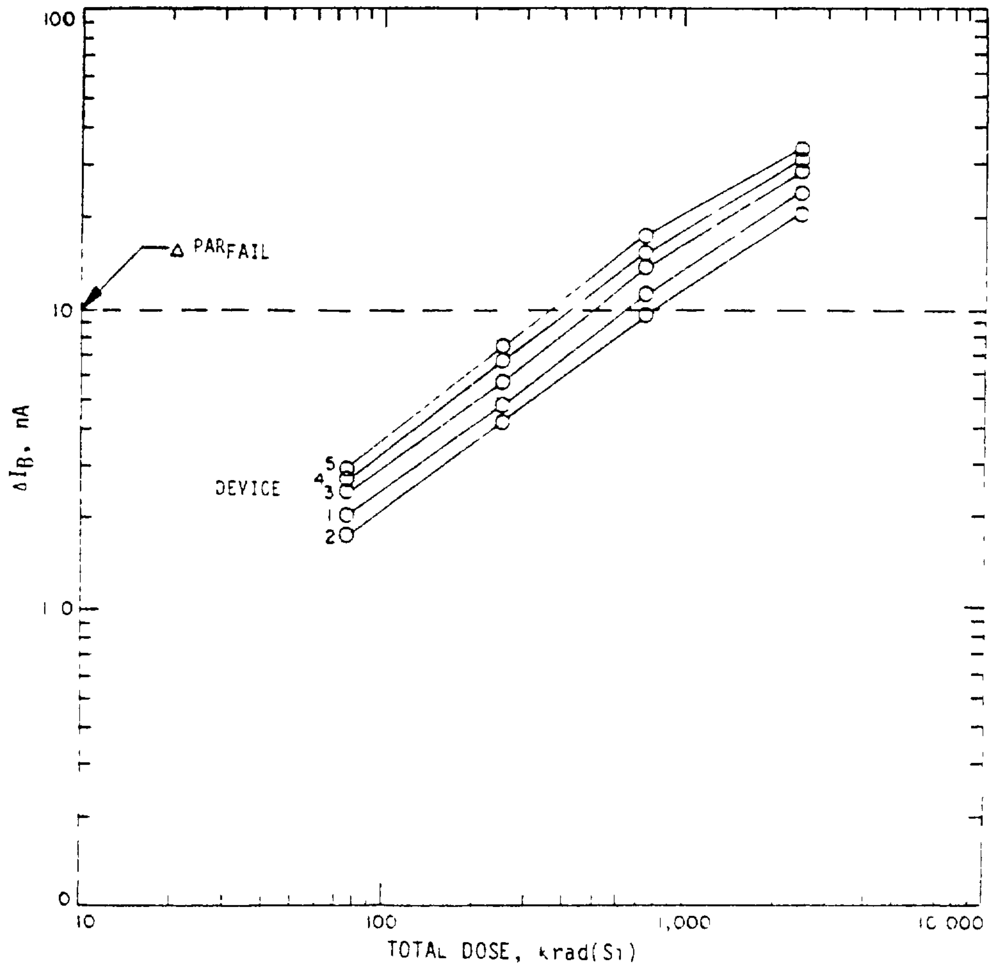

FIGURE 12 ΔI_B vs total dose for LM108 amplifiers

K_{TL} = 6.112 from table XV for n = 5,

c = 90% and P_{DIST} = 99.9%

Therefore, from eq. 5.1.3,

$$PCC = e^{6.112 \times 0.331} = 7.58$$

Step 5 - Categorize the part type as follows:

TDM = 3.5 from Step 3

PCC = 7.58 from Step 4

TDM is less than PCC. Consequently, this part type is categorized as HCC-1M and lot acceptance testing is required.

The data plots shown on figure 12 are approximately linear. Consequently, the lot acceptance test for this part type need be at D_{SPEC} only.

Example 2. Categorization of the 2N2222 transistor on the basis of dc current gain, h_{FE}, for five test parts using D_{FAIL} values.

Let us consider the radiation induced change in the reciprocal of the dc current gain, $\Delta(1/h_{FE})$, at a collector current of 1 mA.

Where

$$\Delta\left(\frac{1}{h_{FE}}\right) = \frac{1}{h_{FE(RAD)}} - \frac{1}{h_{FE(Initial)}}$$

The system in this example has the following requirements: D_{SPEC} = 150 krad(Si); n = 5, C is 95%, and P_{DIST} is 99.9%, for determining PCC; $PAR_{MIN(h_{FE})}$ = 50 as taken from the manufacturer's specification sheet. The worst case circuit failure value, $PAR_{FAIL(h_{FE})}$ is 39 minimum. We then proceed as follows:

Step 1 - Determine the $\Delta(1/h_{FE})$ equivalent to a PAR_{FAIL} value of 39, using the manufacturer's $PAR_{MIN(h_{FE})}$ value of 50:

$$\Delta\left(\frac{1}{h_{FE}}\right)_{FAIL} = \frac{1}{PAR_{FAIL(h_{FE})}} - \frac{1}{PAR_{MIN(h_{FE})}} = \frac{1}{39} - \frac{1}{50}$$

$$\Delta\left(\frac{1}{h_{FE}}\right)_{FAIL} = 0.0055$$

NOTE The value of $\Delta(1/h_{FE})_{FAIL}$ was calculated in this example using the manufacturer's minimum specification $PAR_{MIN(h_{FE})}$ because this is the worst case pre-test acceptance criterion for future lots to be HA tested. For the case where parts are selected for higher h_{FE} values, $\Delta(1/h_{FE})_{FAIL}$ should be calculated using this special selected $PAR_{MIN(h_{FE})}$ value. For the case of lot acceptance testing $\Delta(1/h_{FE})_{FAIL}$ should be calculated using the pre-radiation value of h_{FE}.

Step 2 - Irradiate the test sample in accordance with the requirements of paragraph 4.1 at increasing dose levels until all of the parts have reached the $\Delta(1/h_{FE})_{FAIL}$ value of 0.0055. Plot $\Delta(1/h_{FE})$ versus total dose as shown on figure 13.

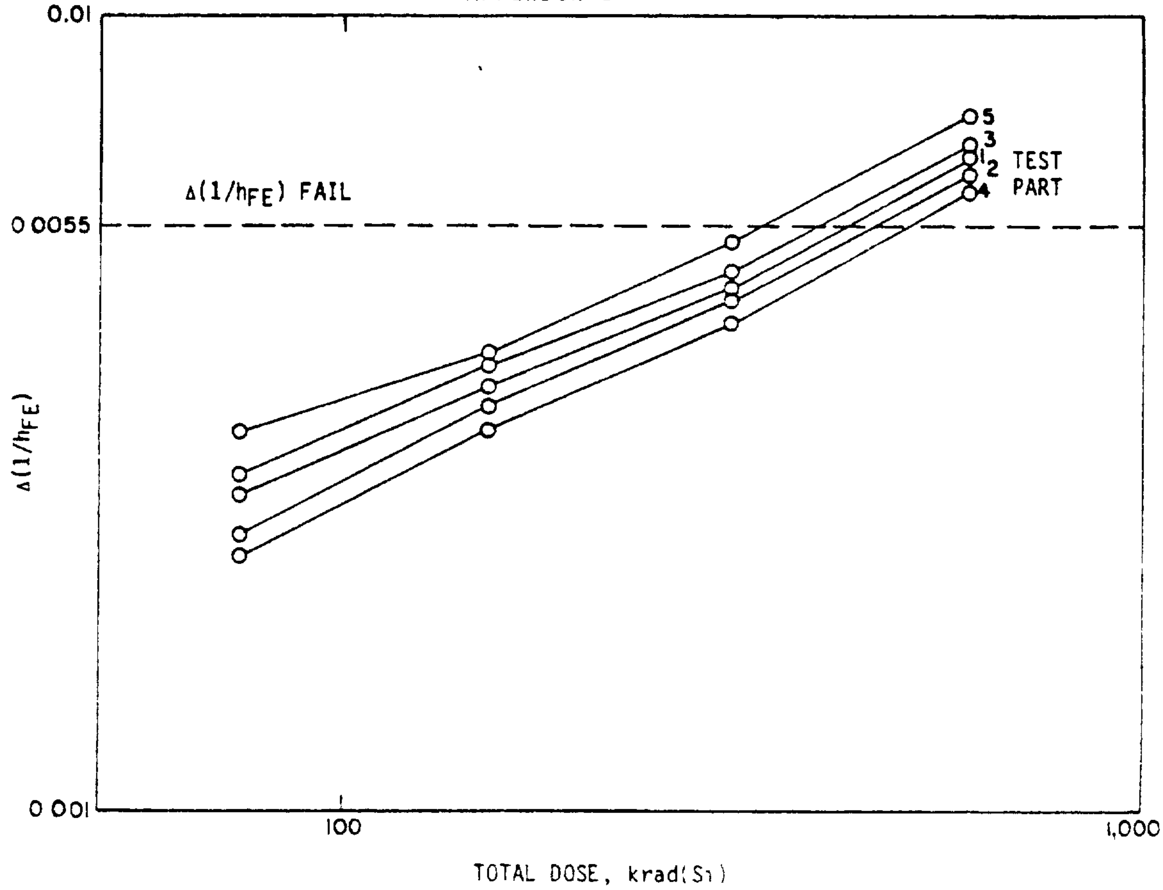

FIGURE 13. $\Delta(1/h_{FE})$ vs total dose for 2N2222 transistors

Step 3 - Determine the total-dose circuit failure value, D_{FAIL}, for each part at the $\Delta(1/h_{FE})_{FAIL}$ value of 0.0055 from figure 13.

Test part	D_{FAIL} in krad(Si)
1	420
2	460
3	390
4	510
5	330

Step 4 - Determine TDM D_{MF}/D_{SPEC} and $s_{ln(D_{FAIL})}$ using the D_{FAIL} values from Step 3.

From eq. 5.1.1,

$$D_{MF} = 418 \text{ krad(Si)}$$

and

$$D_{SPEC} = 150 \text{ krad(Si)},$$

therefore

$$TDM = 418/150 = 2.799$$

and, from eq. 5.1.2,

$$s_{ln(D_{FAIL})} = 0.165$$

Step 5 - Determine PCC using the value of $s_{ln(D_{FAIL})}$ = 0.165 from Step 4 and K_{TL} = 7.501 from table XIII for n = 5, C = 95% and P_{DIST} = 99.9%.
Therefore, from eq. 5.1.3,

$$PCC = e^{7.501 \times 0.165} = 3.46$$

Step 6 - Categorize the part application as follows:

TDM = 2.79 from Step 4

PCC = 3.46 from Step 5

TDM is less than PCC. Consequently, this part application is categorized as HCC-1M and requires lot acceptance testing.

The data plots shown on figure 13 are approximately linear. Consequently, the lot acceptance test for this part application need be at D_{SPEC} only.

Example 3. Categorization of the 2N3637 transistor on the basis of the Collector Leakage Current, I_{CBO}, for a test sample of five parts using PAR_{RAD} values.

The system in this example has the following requirements. D_{SPEC} = 30 krad(Si); n = 5, C = 95%, and P_{DIST} = 99.9%, for determining PCC. The worst case circuit failure value, PAR_{FAIL}, is 30 nA. We then proceed as follows:

Step 1 - Irradiate the test samples in accordance with the requirements of 4.1 at increasing dose levels until all of the parts have reached the PAR_{FAIL} value of 30 nA.

In the course of testing, none of the I_{CBO} values have reached PAR_{FAIL} at 600 krad(Si), which is twenty times the D_{SPEC} value of 30 krad(Si). The plot of this data is shown on figure 14.

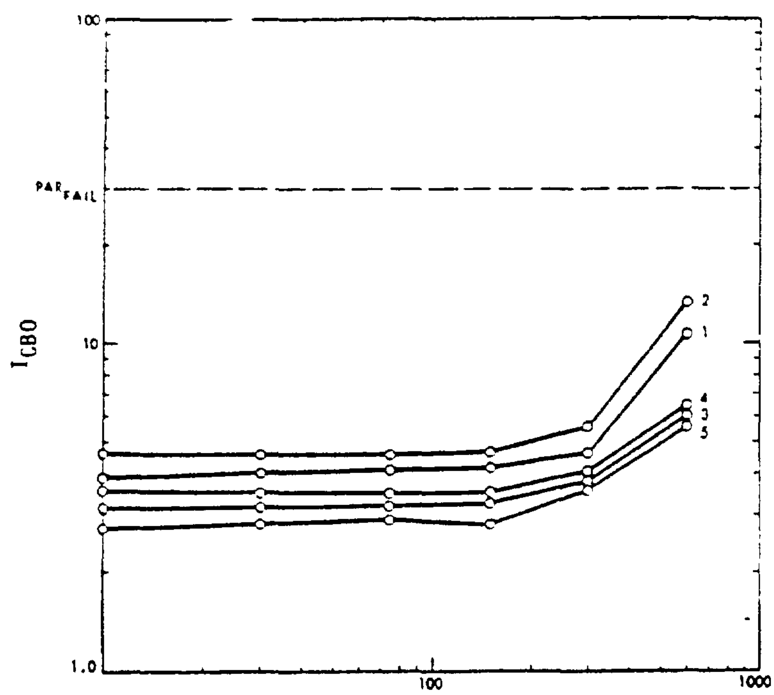

FIGURE 14. I_{CBO} vs total-dose for 2N3637 transistors.

As the D_{FAIL} values cannot be obtained from the graph, the part application cannot be categorized using the methods of examples 1 and 2. One solution to this problem is to use the PAR_{RAD} values at D_{SPEC} and calculate a design margin, DM, based on the PAR_{RAD} values. The value of DM is then used to classify the part type in place of TDM. If DM is equal to or less than PCC the part type is categorized as HCC-1M. If DM is greater than PCC it is categorized as HCC-2. This solution is used in the steps that follows.

Step 2 - Using the follow $PAR_{RAD}(I_{CBO})$ values measured at D_{SPEC} = 30 krad(Si), determine

Test part	$PAR_{RAD}(I_{CBO})$ in nA
1	4.1
2	4.6
3	3.2
4	3.5
5	2.9

$$DM = \frac{PAR_{FAIL}}{e^{\overline{\ln(PAR_{RAD})}}} \quad \text{and} \quad s_{\ln(PAR_{RAD})}$$

for increasing levels where, from eq 5.2.1,

$$e^{\overline{\ln(PAR_{RAD})}} = 3.61 \text{ nA}$$

Therefore

$$DM = \frac{30 \text{ nA}}{3.61 \text{ nA}} = 8.31$$

From eq. 5.2.2,

$$s_{\ln(PAR_{RAD})} = 0.186$$

Step 3 - Determine PCC using the value of $s_{\ln(PAR_{RAD})}$ = 0.186 from Step 2 and

K_{TL} = 7.501 from table XIII for n = 5, C = 95% and P_{DIST} = 99.9%.

From eq. 5.1.3,

$$PCC = e^{7.501 \times 0.186} = 4.04$$

Step 4 - Categorize the part application as follows

DM = 8.31 from Step 2

PCC = 4.04 from Step 3

DM is greater than PCC. Consequently, this part type is classified as HCC-2 and does not require lot acceptance testing.

Although the data plots of figure 14 are not linear above 150 krad(Si), they are linear well above the critical value of D_{SPEC} = 30 krad(Si). Consequently, the sample tests need be carried out at only the single total-dose value of D_{SPEC}.

50.3 Lot acceptance testing. An example of lot acceptance testing at a single total-dose based on the PAR_{RAD} values, and an example of multiple total-dose lot acceptance testing based on the D_{FAIL} values will be presented. As with the previous examples, less than ten parts will be used in order to simplify the presentation.

Example 1 - Lot acceptance test for a 2N2222 transistor on the basis of the Collector Leakage Current, I_{CBO}, at a single dose.

The system in this example has the following requirements, D_{SPEC} = 150 krad(Si); n = 5, C = 95% and P_{DIST} = 99.9%, V_{CB} = 15 V; PAR_{FAIL} = 15 nA.

Step 1 - Irradiate and measure PAR_{RAD} for a random sample of 5 parts from the lot being evaluated, at V_{CB} = 15 V and D_{SPEC} = 150 krad(Si).

Test part	$PAR_{RAD(I_{CBO})}$ in nA
1	0.19
2	0.20
3	0.17
4	0.16
5	0.13

Step 2 - Determine $e^{\overline{\ln(PAR_{RAD})}}$ and $s_{\ln(PAR_{RAD})}$ using the PAR_{RAD} values recorded in in Step 1. From eq. 5.2.1,

$$e^{\overline{\ln(PAR_{RAD})}} = 0.168$$

and, from eq. 5.2.2,

$$s_{\ln(PAR_{RAD})} = 0.169$$

Step 3 - Determine $DM(Lot) = \dfrac{PAR_{FAIL}}{e^{\overline{\ln(PAR_{RAD})}}}$ and $e^{K_{TL} s_{\ln(PAR_{RAD})}}$ for increasing parameter values.

$$DM(Lot) = \frac{15 \text{ nA}}{0.168 \text{ nA}} = 89.3$$

and the lot acceptance criterion is:

$$e^{7.501 \times 0.169} = 3.6$$

for K_{TL} = 7.501, from table XIII, for n = 5, C = 95% and P_{DIST} = 99.9%.

Step 4 - On the basis of the lot acceptance criterion,

$$DM(Lot) \geq e^{K_{TL} s_{\ln(PAR_{RAD})}},$$

evaluate the data:

89.3 is greater than 3.6.

Therefore, this lot of parts is acceptable.

Example 2 - Lot-acceptance test, using fluence-to-failure, for the radiation-induced changes in input bias current, ΔI_B, for an LM101 operational amplifier at a load of 5 mA.

The system has specified the following requirements: D_{SPEC} is 125 krad(Si), n = 6, C = 95%, and P_{DIST} = 99.9%, $\Delta PAR_{FAIL(I_{CBO})}$ = 90 nA.

Step 1 - Irradiate the six test samples in accordance with the system requirements at increasing dose levels until all six devices have reached $\Delta(PAR_{FAIL})$ value of 90 nA. Plot ΔI_B versus total dose as shown on figure 15 for each device.

Step 2 - Determine the total-dose circuit failure value, D_{FAIL}, for each device at the $\Delta(PAR_{FAIL})$ value of 90 nA from figure 15.

Device	D_{FAIL} in krad(Si)
1	1,500
2	1,300
3	1,900
4	1,100
5	1,700
6	1,000

Step 3 - Determine $e^{\overline{\ln(D_{FAIL})}}$ and $s_{\ln(D_{FAIL})}$ using the D_{FAIL} values from Step 2.

From eq. 5.2.3,

$$e^{\overline{\ln(D_{FAIL})}} = 1,380 \text{ krad(Si)}$$

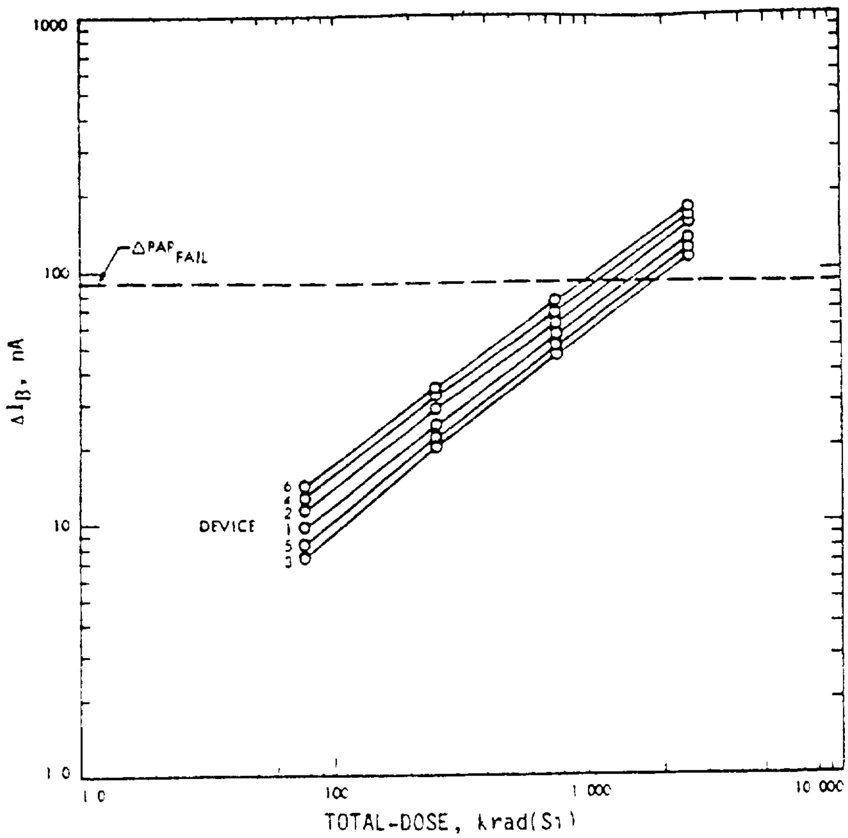

FIGURE 15. ΔI_B vs total dose for LM101 amplifiers

and, from eq. 5.2.4,

$$s_{\ln(D_{FAIL})} = 0.250$$

Step 4 - Determine TDM(Lot) = $\frac{e^{\overline{\ln(D_{FAIL})}}}{D_{SPEC}}$ and $e^{K_{TL}s_{\ln(D_{FAIL})}}$:

$$TDM(Lot) = \frac{1,380 \text{ krad(Si)}}{150 \text{ krad(Si)}} = 9.2$$

and

$$e^{6.612 \times 0.250} = 5.2$$

for K_{TL} = 6.612, from table XIII, for n = 6, C = 95% and P_{DIST} = 99.9%.

Step 5 - On the basis of the lot acceptance criterion,

$$TDM(Lot) \geq e^{K_{TL}s_{\ln(D_{FAIL})}},$$

evaluate the data: 9.2 is greater than 5.2, therefore: this lot of parts is acceptable.

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1. DOCUMENT NUMBER MIL-HDBK-279	2. DOCUMENT TITLE TOTAL-DOSE HARDNESS ASSURANCE GUIDELINES FOR SEMICONDUCTOR DEVICES AND MICROCIRCUITS
3a. NAME OF SUBMITTING ORGANIZATION	4. TYPE OF ORGANIZATION *(Mark one)* ☐ VENDOR ☐ USER ☐ MANUFACTURER ☐ OTHER *(Specify)* ______
b. ADDRESS *(Street, City, State, ZIP Code)*	

5. PROBLEM AREAS

a. Paragraph Number and Wording

b. Recommended Wording

c. Reason/Rationale for Recommendation

6. REMARKS

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MILITARY HANDBOOK

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MIL-HDBK-279, dated 25 January 1985, is hereby canceled. It has been superseded by MIL-HDBK-814, "Ionizing Dose and Neutron Hardness Assurance Guidelines for Microcircuits and Semiconductor Devices".

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