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MILITARY HANDBOOK

IONIZING DOSE AND NEUTRON HARDNESS ASSURANCE GUIDELINES FOR MICROCIRCUITS AND SEMICONDUCTOR DEVICES

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Ionizing Radiation and Neutron Hardness Assurance Guidelines for Microcircuits and Semiconductor Devices

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 8 FEBRUARY 1994 for printing and inclusion in the military standardization handbook series.

3. Every effort has been made to reflect the latest information on nuclear survivability procedures. It is the intent to review this handbook periodically to assure 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: Defense Electronics Supply Center, ATTN: DESC-ECC, 1507 Wilmington Pike, Dayton, OH 45444-5270, by using the 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 to the application of piecepart hardness assurance programs for the effects of ionizing radiation (total) dose and neutron damage to semiconductor electronics. These guidelines are addressed to both program managers and designers of radiation hardened electronics systems. This handbook is a revision and combination of the earlier MIL-HDBK-279 and MIL-HDBK-280.

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1. SCOPE

1.1 Background. Systems that must operate in a radiation environment have to be designed to be survivable (hard) to radiation stress levels specified for them. In addition to design hardening, a Hardness Assurance (HA) program must also be developed during the system design phase for implementation in the production phase. The HA program consists of the production controls and tests which assure that each end product, i.e., delivered system, meets the hardened design specifications and requirements. This handbook is a revision and combination of the earlier MIL-HDBK-279 (see 6.1) and MIL-HDBK-280 (see 6.2) which in turn were the results of earlier work performed under the auspices of the Defense Nuclear Agency ((DNA) see 6.3 and 6.4).

1.2 Overview. Many methods and techniques may be employed at the various electronics design levels (system, subsystem, module and part) to achieve system survivability. This handbook provides HA techniques and procedures applicable to neutron fluence and ionizing radiation dose permanent damage effects on electronic pieceparts. (This damage is considered permanent even though some annealing may occur.) Sufficient information is provided to relate part level HA to the overall system's HA program. Complete procedures are provided for the application of two piecepart HA methods, the Design Margin Breakpoint (DMBP) method and the Parts Categorization Criterion (PCC) method. The DMBP method does not provide a mathematical basis from which statistical survivability inferences may be drawn for the individual part types. There is also a risk involved in that the device response dispersion is not taken into account. The PCC method is mathematically rigorous and applies single-sided cumulative distribution statistics with relationship to survivability requirements and sample size. The PCC method is somewhat more difficult to apply than the DMBP method, but is applicable to any system and provides a sound statistical basis for piecepart survivability estimates. Both methods apply defined design margins and categorization procedures for piecepart control and testing.

1.2.1 Objective. The intent of this document is to provide the methodology and procedures applicable to the DMBP and PCC electronic pieceparts radiation HA methods. Both methods have been applied to systems currently in production or in the DoD inventory. An important goal of this handbook is to promote the standardization of HA procedures. Standardization is of great benefit in establishing program adequacy and reducing costs in that new and untried procedures need not be developed for each systems program. Having a basic, standardized program is also important to maintenance organizations where numerous systems must be maintained over their operational lifetimes.

1.2.2 Scope. This document addresses the piecepart level system engineering approach to the implementation of an HA program applicable to both neutron and ionizing radiation (ionizing dose) permanent damage derived from nuclear weapon or natural space environments. Recommendations are included for systems with low to moderate requirements (DMBP method) and for moderate to severe requirements (PCC method). A system of parts categorization based on design margin is presented which provides consistency in parts qualification procedures and control requirements. Information is provided on sampling and sample sizes, test facilities, qualification and lot acceptance testing, and documentation requirements. Recommendations are made for the use of pieceparts available under the Government sponsored Radiation Hardness Assured (RHA) device program. Information is also included on peripheral subject matter that is necessary or helpful to an understanding of these guidelines.

1.2.3 Users. This handbook is directed primarily toward the systems contractors, Systems Program Offices (SPOs) and Program Executive Offices (PEOs) that are responsible for developing electronic equipment which is hardened to specified radiation environments and has a corresponding HA program.

1.3 Limitations. These guidelines address only permanent or semipermanent damage to electronic pieceparts resulting from ionizing radiation dose or neutron displacement damage. It does not deal with transient effects occurring as a result of highly ionizing, short duration pulses of gamma or x rays, (i.e., prompt dose rate effects).

1.3.1 DMBP limitations. It should be noted that the DMBP method described herein, though initially based on statistical considerations, is not mathematically rigorous. The method is related to the mean of a sample distribution rather than the dispersion or standard deviation of the particular test sample. Though the recommended breakpoints are generally considered conservative, a risk factor must be assumed since the actual deviation about the mean is not taken into consideration for each device type. The method, however, is particularly useful when the specification requirements (radiation stress levels and survivability and confidence factors) are moderate.

2. REFERENCED DOCUMENTS

2.1 Government documents.

2.1.1 Specifications, standards and handbooks. The following specifications, standards and handbooks of the latest issue (see Department of Defense Index of Specifications and Standards - DODISS) form a part of this specification.

SPECIFICATIONS

MILITARY

MIL-S-19500	-	Semiconductor Devices, General Specification for
MIL-H-38534	-	Hybrid (Custom) Microcircuits, General Specification for
MIL-I-38535	-	Integrated Circuits (Microcircuits) Manufacturing, General Specification for

STANDARDS

MILITARY

MIL-STD-100	-	Engineering Drawing Practices
MIL-STD-105	-	Sampling Procedures and Tables for Inspection by Attributes
MIL-STD-202	-	Test Method for Electronics and Electrical Component Parts
MIL-STD-414	-	Sampling Procedures and Tables for Inspection by Variables for Percent Defective
MIL-STD-454	-	Standard General Requirements for Electronic Equipment
MIL-STD-750	-	Test Methods for Semiconductor Devices
MIL-STD-883	-	Test Methods and Procedures for Microcircuits
MIL-STD-1546	-	Parts, Materials, and Process Control Program for Space Launch Vehicles
MIL-STD-1547	-	Electronic Parts, Materials and Processes for Space Launch Vehicles
MIL-STD-1562	-	Lists of Standard Microcircuits

HANDBOOKS

MILITARY

MIL-HDBK-339	-	Custom Large Scale Integrated Circuit Development and Acquisition for Space Vehicles
MIL-HDBK-780	-	Standardized Military Drawings
MIL-HDBK-816	-	Guidelines for Developing Specifications for Radiation Hardness Assured Devices.

(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, ACRONYMS AND SYMBOLS

3.1 Definitions. In addition to the definitions specified in MIL-I-38535, appendix A, the following definitions apply:

3.1.1 Characterization testing. - See Qualification Testing, 3.1.28.

3.1.2 Confidence level. (C) is the chance of rejecting a lot where there is less than probability P that any part from the lot can pass the test conditions.

3.1.3 Cumulative proportion. (P_{DIST}) is the fraction or proportion of a probability distribution which is below a given upper limit (or above a given lower limit). P_{DIST} thus corresponds to the probability that a parameter is below a given upper limit (or above a given lower limit). The cumulative distribution function is an example (see appendix 50.1.2.2).

3.1.4 Design margin breakpoint (DMBP) method. A method of categorizing electronic pieceparts for control purposes. The piecepart design margin is compared to given DMP values to categorize the part type and, in turn, the category dictates the control requirements.

3.1.5 Device. A general term frequently used interchangeably with piecepart.

3.1.6 In-flux testing. The test device electrical parameter measurements are made in-situ while the test device is in the radiation field.

3.1.7 In-situ testing. The test device electrical parameter measurements are made during or before and after irradiation, while the test device remains in the irradiation location.

3.1.8 Ionizing radiation dose. Ionizing radiation dose accumulated over a period of time. A terminology used interchangeably with ionizing dose but considered a more appropriate expression to relate implied cumulative dose.

3.1.9 Lot. The population of parts from which a sample has been taken (see MIL-I-38535, appendix A).

3.1.10 Lot acceptance testing (LAT). LAT is the testing of a sample of parts from a procurement lot to determine if the lot is acceptable. LAT refers to radiation testing, or quality conformance inspection.

3.1.11 Lot size. (N) is the number of parts in the lot before the test sample has been removed.

3.1.12 Mean parameter value, lognormal distribution.

$$[PAR_{RAD}]_m = e^{\overline{\ln(PAR_{RAD})}}$$

3.1.13 Mean radiation level to failure, lognormal distribution.

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

3.1.14 Measured logarithmic mean for PAR_{RAD}.

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

3.1.15 Measured logarithmic mean for R_{FAIL}. *

$$\overline{\ln(PAR_{FAIL})} = \frac{1}{n}\sum_{i=1}^{N} \ln(PAR_{FAIL_i})$$

3.1.16 Measured logarithmic standard deviation for PAR_{RAD}.

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

3.1.17 Measured logarithmic standard deviation for R_{FAIL}.

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

3.1.18 Measured normal mean for PAR_{RAD}.

$$\overline{PAR_{RAD}} = \frac{1}{n}\sum_{i=1}^{n} PAR_{RAD_i}$$

3.1.19 Measured normal standard deviation for PAR.

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

* Expressions with an "i" subscript are the parameter value measurements for the i^{th} device.

3.1.20 Neutron fluence - is the total number of neutrons per square centimeter incident at the position of interest. For neutron effects on silicon electronics, the fluence is generally stated in terms of 1 MeV Silicon Damage Equivalence (SDE). See ASTM standard E722 for a more compete definition.

3.1.21 Nonstandard parts. See standard parts.

3.1.22 One-sided tolerance limit (K_{TL}). If n values of parameter PAR are measured and PAR is normally distributed, then, for situations where PAR must not exceed an upper limit, (PAR_{MAX}), with confidence C, there is at least a probability, P_{DIST}, that the parameter in the parent population is less than

$$\overline{PAR} + K_{TL}(n, c, P_{DIST})\, s_{(PAR)}\,.^{+}$$

\+ Do not confuse this sampling statistics confidence with Bayesian confidence. A more precise statement for sampling statistics is that, if an indefinitely large number of tests were performed, each drawing n samples from the same normal population, then in fraction C of the tests one-sided tolerance limit

$$\overline{PAR} + K_{TL}(n, c, P_{DIST})\, s_{(PAR)}$$

would exceed the P_{DIST} fractile of the distribution. This quantity does not by itself predict a possibility for where the P-fractile actually lies. For example, other information might give the location of the P_{DIST} fractile so there would be 100 percent confidence in whether or not a given quantity exceeded that fractile. Yet, each time the test was performed, there would still be a probability C prior to the test that the one-sided tolerance limit, calculated as above, would exceed the P_{DIST} fractile. Strictly speaking, the one-sided tolerance limit is compared with an acceptable parameter limit, PAR_{LIM}, in a lot acceptance test and defective shipments are rejected with confidence C. When justified by expert judgement, the one-sided tolerance limit may be used to estimate how far a design parameter should be allowed to vary when using parts from the tested lot. The one-sided tolerance limit from a single lot should not be used as a parameter limit criterion for testing future lots unless you are prepared to reject about half of all future lots.

Likewise, with confidence C, for situations where PAR must not exceed a lower limit, (PAR_{MIN}), there is at least a probability, P_{DIST}, that the parameter in the parent population is greater than

$$\overline{PAR} - K_{TL}(n, c, P_{DIST})\, s_{(PAR)}$$

3.1.23 Parameter design margin (lognormal distribution). For parameter values that increase with radiation

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

and for parameter values that decrease with radiation

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

3.1.24 Parameter failure value. PAR_{FAIL} is the value of a particular parameter for the device under evaluation at which failure occurs.

3.1.25 Part categorization criterion (PCC) method. A statistical categorization method applied to a system's electronic pieceparts. The design margin of each piecepart type is compared to a PCC value to determine the hardness critical category and resultant control requirements.

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

3.1.27 Pieceparts. Electrical or electronic devices, including semiconductor diodes, transistors and integrated circuits.

3.1.28 Qualification testing. This is the testing whereby sufficient parametric (characterization) radiation response data are developed to establish an acceptable baseline indicating that the piecepart type meets the acceptance criteria for application in the system.

3.1.29 Radiation design margin (lognormal distribution).

$$RDM = \frac{R_{MF}}{R_{SPEC}} = \frac{e^{\overline{\ln(R_{FAIL})}}}{R_{SPEC}}$$

3.1.30 Radiation fluence or dose to failure. R_{FAIL} is the neutron fluence value or the total ionizing dose value for the part under test at which PAR_{RAD} equals PAR_{FAIL}.

3.1.31 Radiation hardness assured (devices). These are semiconductor devices manufactured to MIL-STD (JAN) specifications that are assured hard to specific ionizing dose and neutron fluence levels as specified in the MIL-STDs.

3.1.32 Radiation mean failure (lognormal distribution).

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

3.1.33 Radiation-induced parameter value. PAR_{RAD} is the parameter value at a particular dose or fluence level.

3.1.34 Remote testing. Preceding or following irradiation or an irradiation step, the test device is removed from the radiation cell to another location for electrical characterization testing.

3.1.35 Sample size. (n) is the number of pieceparts, selected at random from the lot, that are to be tested.

3.1.36 Specified radiation level. R_{SPEC} is the maximum neutron fluence or ionizing dose which the circuit under consideration must survive.

3.1.37 Standard parts. Standard parts for application of this handbook are JAN, QML and SMD devices (MIL-STD-883, section 1.2.1 compliant devices may also be considered standard devices if the SPO/PEO agrees to it). For ICs, these are, in order of preference, JAN/RHA, JAN, SMD (and possibly MIL-STD 883 compliant devices). For transistors, these are JAN/RHA, JAN and DESC Drawing devices. Parts not available under these criteria are considered nonstandard devices.

3.1.38 Time dependent effects (TDE). TDE a terminology most often applied to ionizing radiation induced damage. TDE takes into consideration the damage incurred as a function of time, radiation deposition rate, defect growth and annealing, both concurrent with the irradiation and following irradiation to a time of interest.

3.1.39 Ionizing dose. See definition 3.1.8.

3.1.40 Vendor. A vendor is a manufacturer of electrical/electronic parts.

3.2 Acronyms and symbols.

AF	Air Force
ARL	Army Research Laboratory
ASTM	American Society for Testing and Materials
C	Confidence Level
CCB	Configuration Control Board
Co-60	Cobalt-60
DASIAC	DoD Nuclear Information and Analysis Center
DESC	Defense Electronic Support Center
DI	Dielectrically Isolated
DID	Data Item Description
DM	Design Margin (can be PDM or RDM)

DMBP	Design Margin Breakpoint
DNA	Defense Nuclear Agency
ERRIC	Electronics Radiation Response Information Center
F	Cumulative Standard Normal Distribution
$\tilde{F}$	Antifunction of F
FBR	Fast Burst Reactor
FSED	Full Scale Engineering Development
f_T	Gain-bandwidth Product (Hz)
Gy	Gray - A Measure of Deposited Energy (1 J/kg)
HA	Hardness Assurance
HADD	Hardness Assurance Design Documentation
HC	Hardness Critical
HCC	Hardness Critical Category
HCI	Hardness Critical Item
HCP	Hardness Critical Process
HDI	Hardness Dedicated Item
HM	Hardness Maintenance
HNC	Hardness Noncritical
HS	Hardness Surveillance
I_B	Bias Current (A)
IC	Integrated Circuit
JAN	Joint Army/Navy
K_{TL}	One Sided Tolerance Limit Factor
LAC	Lot Acceptance Criteria (or Criterion)
LAT	Lot Acceptance Test
LINAC	Linear (Electron) Accelerator
LWC	Limited Worst Case
MIL-STD	Military Standard
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
N	Lot Size
n	Sample Size
NASA	National Aeronautics and Space Administration
PAR	Device Parameter Value
PAR_{FAIL}	Parameter Failure (or Change in) Value
PAR_{RAD}	Radiation Induced Parameter (or Change in) Value
PCB	Parts Control Board
PCC	Part Categorization Criterion
P_{DIST}	Cumulative Proportion of Distribution
PDM	Parameter Design Margin
PEO	Program Executive Officer
P_S	Probability of Survival
QA	Quality Assurance
QCI	Quality Conformance Inspection
rad	Measure of Deposited Energy (100 ergs/g)
RDM	Radiation Design Margin
RDT&E	Research, Development, Test and Evaluation
R_{FAIL}	Fluence or Dose to Failure
RHA	Radiation Hardness Assured
R_{MF}	Mean Radiation (Fluence or Dose) Failure Level
R_{SPEC}	Radiation Specification Level

SCD	Specification Control Drawing
SSD	Sample Standard Deviation
SDE	Silicon Damage Equivalence
Si	Silicon
SID	Selected Item Drawing
SOCD	Source Control Drawing
SPO	System Program Office
SPWG	Space Parts Working Group
S/V	Survivability/Vulnerability
TDE	Time Dependent Effects
TRIGA	A Type of Water Moderated Nuclear Reactor
TLD	Thermoluminescent Dosimeter
V_{th}	Threshold Voltage
X_{Li}	Lot End-point Limit
X_{LL}	Multi-lot End-point Limit

4. GENERAL HARDNESS ASSURANCE REQUIREMENTS

4.1 Radiation Environments and Effects. This section presents general information on the radiation environments and piecepart radiation response relevant to these guidelines. This information is only introductory, and the reader is referred to sections 6.5 through 6.9 and the IEEE Transactions on Nuclear Science for additional information. Subjects briefly discussed here include: radiation threat considerations; the nuclear weapon generated ionizing radiation and neutron environments; the natural space ionizing radiation environment; the basic permanent damage responses of semiconductor devices to these environments; and the resultant specifications to be addressed.

4.1.1 Threat considerations. Typical threats resulting in the radiation environments relevant to this handbook include the following:

a. Endoatmospheric nuclear weapons environment--The weapon prompt and delayed (i.e., neutron induced secondary) gammas are delivered within one second. These gamma pulses arrive first, followed shortly by the neutrons at a time dependent on their kinetic energy. X-rays are readily absorbed in the atmosphere and are usually not considered an endoatmospheric threat except for very high altitudes. Radio-active debris and fallout must be considered as necessary with respect to the system requirements.

b. Exoatmospheric nuclear weapon environment--The weapon prompt output is the same as for the endoatmospheric-case. X-rays can be a significant threat in this case since there is no atmospheric absorption. Debris and fallout are usually not relevant to this case, except for possibly increased electronics (particularly electro-optics) electrical noise derived from radioactive debris plating on external surfaces.

c. Near-earth orbit space environment--Mainly the Van Allen radiation belts containing trapped high energy electrons and protons can, at a low dose rate, produce a large, ionizing dose buildup over several years of satellite mission time, or at a somewhat higher dose rate from nuclear weapon enhanced trapped electrons over days to years.

d. Space probe environment (e.g., Jupiter)--The significant dose is usually accumulated within several hours time at some point in the mission. Other ionizing dose producing environments that space probes encounter are, the solar wind, solar flares and cosmic rays.

4.1.2 Ionizing radiation environments. The ionizing radiation addressed here consists of x-rays, gamma rays and electrons, though other sources, such as secondary gammas (neutron induced), protons, and cosmic rays may also be relevant. The ionizing radiation criteria for systems survivability must take into account all relevant sources of ionizing radiation, their spectra and periods of delivery in the mission, and the rates of deposition (dose rates). In addition, any shielding of the electronics, particularly for x-rays, electrons and charged particles, must be taken into consideration.

4.1.2.1 Ionizing dose criteria. The ionizing radiation dose criterion is generally related to the silicon in semiconductor electronics, and is expressed in terms of Grays-silicon (Gy(Si)) or rads-silicon (rads(Si)).* If the device or portion of the device of interest is not silicon, then the appropriate absorbed dose must be calculated. Actually, for most Integrated Circuits (ICs), it is usually the dose in the oxides, i.e., rads(SiO_2) that is important, but the difference between the oxide dose and the silicon dose is usually relatively small and is often neglected. Measurement of the absorbed dose must be made for each species of incident radiation. The cumulative (or total) dose is the summation of all acquired doses over the period of time relevant to the mission. (This may include any dose acquired prior to the period that is normally considered the mission.) Ionizing dose includes any contributions from nuclear weapon radioactive clouds and debris, fallout, and

* 100 rads(Si) = 1 gray(Si)

any space related environments such as Van Allen belt electrons, high energy cosmic particles, etc. The ionizing dose specification in the past typically consisted of only the cumulative dose value. However, it is now recognized that time dependent effects can be significant and it is necessary to take into consideration both the dose delivery rates and the delivery times as related to the mission requirements (see 6.10 through 6.14).

4.1.3 Ionizing radiation effects. Ionization, produced by either photon or particulate radiation, results in free carriers (electrons and holes) in electronic materials. This is generally of greatest significance in semiconductor devices where free carriers may recombine or move in accordance with the applied electric fields. The primary ionizing dose problem is with ICs, and in particular, is related to the oxides and the interfaces between the oxide insulators and the semiconductor materials. The mobility of the free electrons is much greater than that of the holes in the oxide and thus the electrons can be swept out by the electric field, leaving many of the holes trapped in the oxide. This is most important in Metal Oxide Semiconductor Field Effect Transistor (MOSFET) technology ICs where the gate oxide acquires a positive charge due to retention of the holes and where negative charge is trapped in defect sites at the oxide/semiconductor interface boundary.

4.1.3.1 TDE. The generation of bulk and interface trapped charge, the charge mobility and recombination, saturation of trapping sites and annealing are complex, manufacturing process dependent phenomena and are not discussed here in detail. However, each phenomenon has a characteristic TDE generation and decay rate which is strongly dependent on manufacturing processes. It is important to note that the resultant radiation responses in MOSFETs are not necessarily predictable, and that characterization testing is necessary. Test results may vary with device biasing, continuous or step stress testing, the dose rate and the time and temperature history from initial irradiation through parameter measurements. Device failure may be the result of graceful degradation to unacceptable parameter values or may be due to abrupt functional failure occurring between two measurement points (see 6.15).

4.1.3.1.1 Gate oxide threshold voltage. One of the most significant MOSFET parameters affected by ionizing dose is the gate threshold voltage, Vth. The time dependent net oxide and interface state charge resulting from both the initial damage and annealing can shift Vth (or other parameters) in either a positive or negative direction which can render the device inoperable in a particular circuit application. Annealing is generally understood to be a reduction of the radiation induced damage as represented by curves (1) and (2) on figure 1 (see 6.16). Curve 1 indicates recovery following irradiation to an operable state while the device represented by curve 2 does not reach an operable state in the time shown. In other cases, annealing will take place in the normal direction of recovery, but the parameter may recover to a value in excess of the initial (nonirradiated) value: this is often called super-recovery or rebound. Curve (3) shows rebound to within device operational limits, and curve (4) depicts rebound to an out-of-tolerance positive value. Negative or reverse anneal has also been observed, and is indicated in curve (5) where, following irradiation, the parameter continues to change in the same direction observed for the initial damage. The curves are representative only, and actual device anneal rates and magnitudes must be determined through testing.

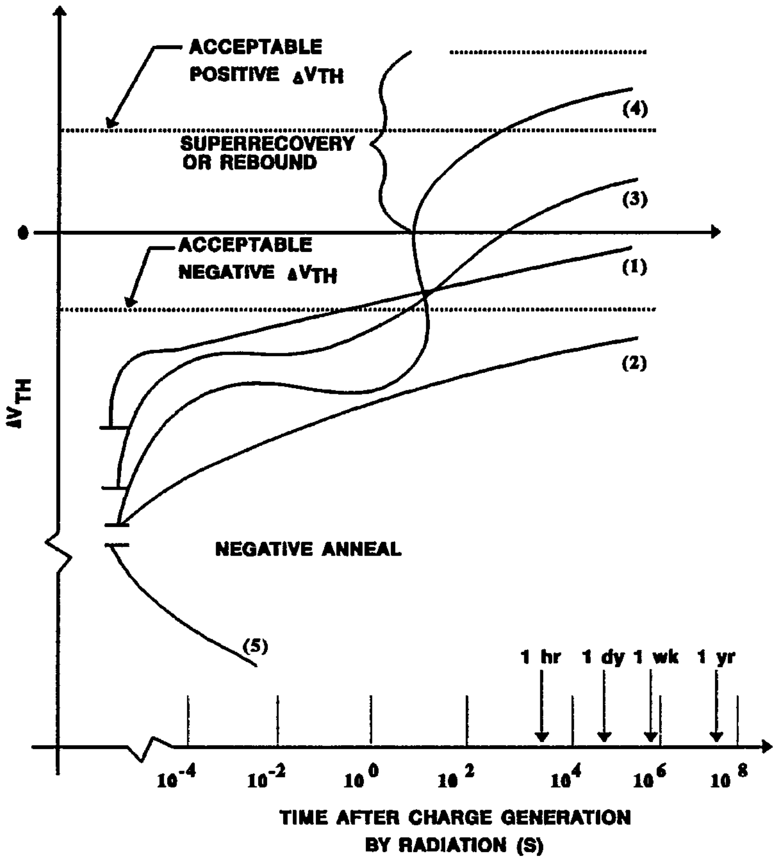


FIGURE 1. MOSFET ionizing dose annealing response.

4.1.3.1.2 Causes of TDE variation. The variations in device response to ionizing radiation TDE can be related to the total accumulated dose and the dose rate or rates at which the devices were exposed and the time between exposure and measurement. For high dose rate environments (rapid dose deposition), the post radiation annealing can be significant though of a complex nature. For very low dose rates, typically, some annealing will occur concurrent with the radiation which can result in a smaller parameter change per unit dose than if exposed to the same dose at a higher dose rate, though the opposite effect has also been observed. Annealing of the radiation damage is both time and temperature dependent. Higher temperatures accelerate annealing, and lower temperatures slow annealing. The extent of damage and annealing depends on the device technology, fabrication processing and the temperature and bias history to the time of measurement.

4.1.4 Neutron radiation environment. The neutron environment considered here is related to nuclear weapon detonations. Since damage in semiconductors is related to the kinetic energy of the incident neutrons, the incident field energy spectrum must be taken into account. For interpretation of effects in electronics, the neutron spectrum is normalized to a monoenergetic 1 MeV fluence that would produce damage in silicon equivalent to the actual neutron spectrum (see 6.17). Thus, the neutron criterion is typically expressed in terms of neutrons per square centimeter (n/cm^2), 1 MeV Silicon Damage Equivalence (SDE). Typically, the time in the mission of neutron deposition is not specified. (This may not hold true where multiple bursts are specified.) When burst timing is not specified, it is generally assumed for hardening purposes that the fluence is acquired at the beginning of the mission. Protons and electrons can also produce displacement damage. It has been shown that displacement damage from all high energy particles depends only on the energy going into atomic processes. It is useful therefore to convert the spectra and fluence of electrons and protons to an equivalent 1 MeV neutron fluence and then the extensive neutron data base can be used or simulation testing can be done in FBR's.

4.1.5 Neutron radiation effects. Neutron radiation degrades the electrical characteristics of semiconductor devices by increasing the number of trapping, scattering and recombination centers in the semiconductor material. Trapping centers remove majority carriers from the conduction process, scattering centers reduce carrier mobility and recombination centers decrease minority carrier lifetime. These effects are most pronounced in bipolar devices since their performance is particularly dependent on minority carrier lifetime in the base region. Usually, graceful degradation of device electrical parameters is observed but abrupt functional failure can be encountered in complex ICs. Generally the most significant observed effect is a reduction in the transistor forward current transfer ratio, or gain. Also, changes in the transit time, junction saturation voltage, breakdown voltage, and bulk resistivity can be significant in some applications. Bipolar devices having low gain-bandwidth products (f_T), such as power devices, are more sensitive to neutron damage than are low power, high frequency devices. MOSFETs are majority carrier devices and are less affected (i.e., harder) than bipolars.

4.1.5.1 Neutron damage annealing. The annealing of neutron induced damage in bipolar devices is usually straight-forward in that the annealing is in a direction toward pre-radiation parameter values (see 6.18). Both higher temperatures and larger current injection promote faster annealing. Most neutron effects data are taken at room temperature and typically show that about half the damage will anneal out within tens of milliseconds when operated at a moderate current level. Short term annealing, between arrival of the neutron pulse and tens of milliseconds is less well defined (see 6.19). It is likely that the damage in this region may be a factor of 3 to 10 times more severe. If it is required to operate through this period, testing should be performed to determine the short term annealing characteristics.

4.1.5.2 Minimum neutron fluence. Because neutron damage in silicon bipolar transistors is well understood, it is possible on the basis of a worst case transistor model to calculate that for neutron fluences of 10^{11} n/cm^2 (1 MeV SDE) or below, silicon transistors with an f_T greater than 5 MHz, and digital and virtually linear ICs will not suffer significant degradation of performance. For a neutron fluence less than 10^{11} n/cm^2, silicon bipolar and MOSFET devices, both integrated and discrete, may be considered to be hardness noncritical parts . Possible exceptions include special high power devices, electro-optical devices, and those devices used in special or extreme precision applications.

4.1.6 Low, moderate and severe requirements. For purposes of describing the application of HA programs presented in this document, the hardening-HA design requirements are divided into three arbitrary regions: low level, moderate and severe. These regions are based on the severity of the radiation specifications and survival requirements with consideration of the hardening difficulties and costs. Both increasingly severe radiation specifications and increased probability of survival requirements tend to exacerbate the hardening problem and increase the hardening and HA costs.

4.1.6.1 Low. For some systems, operational and threat analyses result in radiation levels that are quite low, often approaching what would be considered off-the-shelf inherent hardness levels for unhardened equipment. These would be considered low level systems. However, if applied as specifications on a system, the hardening and HA problems must be worked with consideration of the survival requirements levied on the system. The DMBP approach is generally adequate for these low level applications.

4.1.6.2 Moderate. Moderate requirements systems fall in the region above low level and below severe requirements. These include many man-related systems, such as aircraft, ship, field equipment, and some tactical and small missile systems. These systems tend to fall below the hardness environmental limits associated with personnel radiation factors and blast induced damage to equipment and structures. These bounds keep the radiation levels within the moderate to low level region. Radiation level M of the RHA parts specifications is representative of the upper bound of moderate radiation levels, though consideration must be given to the system's survival requirements, usage, functional requirements, electronic technology employed, etc. The probability of survival, P_S, and confidence, C, typically associated with moderate requirements systems at the piecepart level are generally no greater than 99 percent and 90 percent respectively. Either the DMBP or the PCC method, or both methods used in combination, may be applied to systems with moderate requirements.

4.1.6.3 Severe. For radiation levels above the RHA-M levels and/or for stringent survivability requirements, the hardening and HA tasks should be considered to fall within the severe requirements region, and the PCC method would usually be applied. For some stringent survivability cases, some generic classes of devices may typically be inherently hard (e.g., neutron effects on high speed switching diodes) and the DMBP method may be adequate.

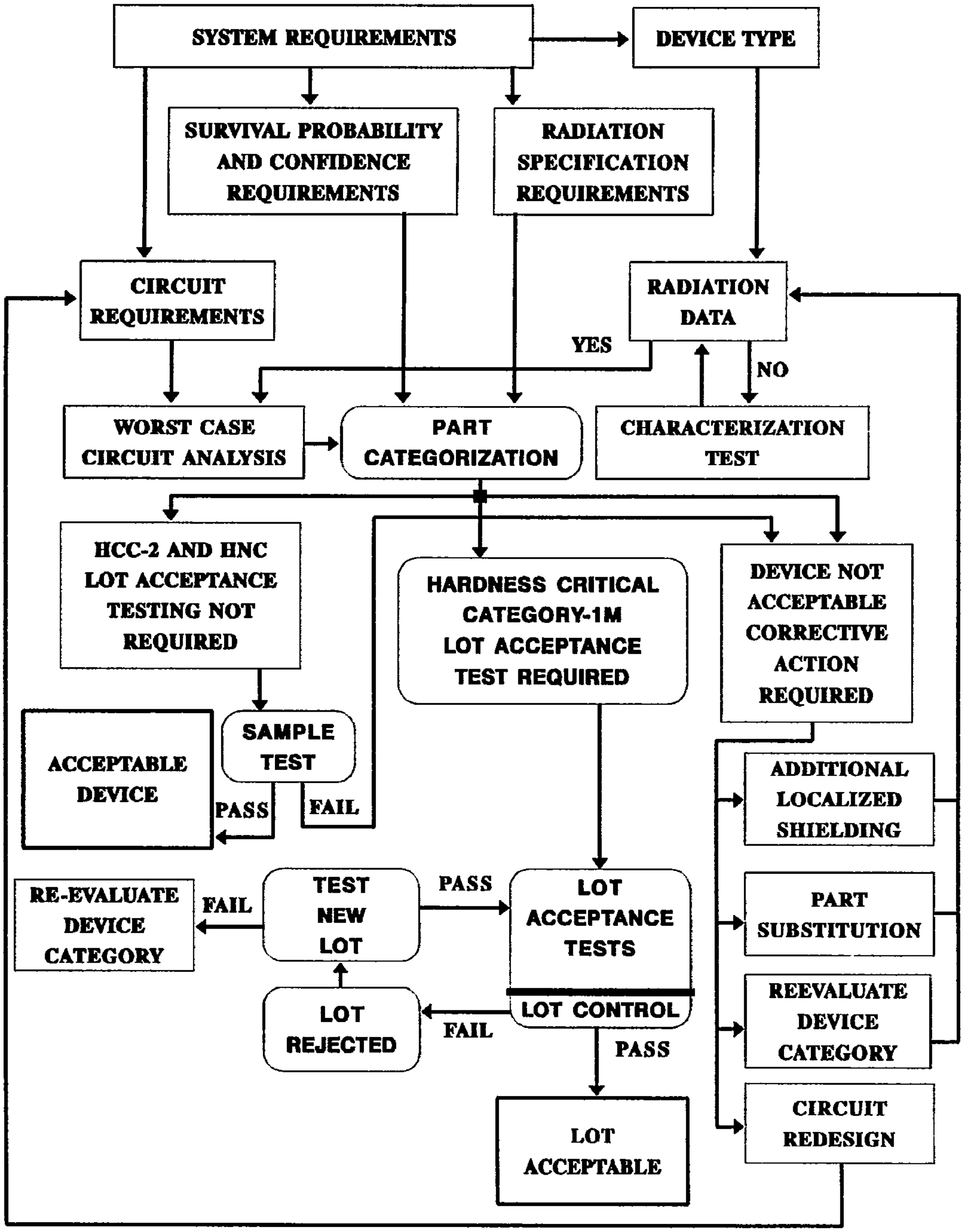
The recommended procedure is first to apply the DMBP method and then to reevaluate any small DM devices using the PCC method with additional test data.

5. DETAILED HARDNESS ASSURANCE REQUIREMENTS

5.1 Radiation design hardening. This section presents an overview of the system radiation design hardening activities which are necessary to the development of a hardened (survivable) system and a corresponding electronics piecepart HA program. Design hardening is the term used to describe the techniques and procedures applied to the system design to provide adequate or increased hardness, and must be carried out as a part of the normal design process. Design hardening goals must be directed toward establishing significant design margins (DMs, i.e., safety margins) for reduced testing and control requirements. These DMs are then related to the categorization procedure and the associated testing and control requirements.

5.1.1 Included activities. Design hardening activities include: radiation testing for parts characterization data and parts qualification; worst-case circuit analyses to determine failure levels and design margins; determination of the procurement requirements for each part; specifying acceptance requirements for any parts requiring lot acceptance testing; and development of the Hardness Assurance Design Documentation (HADD) information necessary to carry out the HA program. The HADD information is required to ensure that the radiation hardness designed into the system is maintained during production and for any future reprocurement of pieceparts. Figure 2 is a representative piecepart assessment flow diagram for a hardened system.

5.1.1.1 Guideline document. As a part of the design/development program, the contractor should prepare a design guideline document for their engineering personnel. This is especially appropriate in the area of electronics design where a commonality of approach is almost essential to an affordable program. Guidelines for parts selection can be developed for a given set of system operational and functional requirements, nuclear specification levels and HA approach. Engineering guidelines should: recommend and restrict the use of particular semiconductor technologies or part types; provide guidance in parts selection; present recommended design approaches (e.g., derating, current limiting, operating voltages and biases, reset capabilities, etc.); and provide preferred approaches to HA, such as acceptable DMs and their derivation.



For Non-RHA parts. Hardness assurance fuctions in rounded areas.
FIGURE 2. Typical system design hardening and hardness assurance flow.

5.1.2 Goal. The goal of radiation design hardening is to select parts and design the circuits so as to minimize the total life cycle costs while also meeting the hardness requirements and providing for an adequate HA program. For example, it may be less costly in the long run to specify a more expensive, less radiation susceptible part type or to increase the complexity of a circuit if it allows the elimination of expensive lot acceptance testing.

5.1.3 HA expertise. The HA program and its technical detail should be interpreted and applied by radiation effects specialists and be incorporated as early in the design stages of the program as practicable. Many contractors have nuclear effects groups within the company that provide adequate capabilities. If the contractor has limited (or no) experience in this area, additional detailed guidance may be obtained from radiation effects consulting firms and individuals. Such specialists can be helpful in providing current radiation effects information regarding parts selection and application, and can serve as consultants for the many special problems that arise during design hardening and the development of an HA program. Additional guidance may also be obtained by contacting Government agencies such as the Defense Nuclear Agency (DNA) electronics effects division, the Army's Nuclear Effects Support Team (NEST) at the Army Research Laboratory, Adelphi, MD; the Air Force Phillips Laboratory, NTC, Kirtland AFB, NM; or the Naval Surface Warfare Center (NSWC), Crane, IN, or White Oak, MD.

5.1.4 Worst-case circuit analysis. A worst case circuit analysis of each circuit in each mission critical system is required for a determination of the electrical failure level of each semiconductor part in each "socket" location, and for an evaluation of the resultant circuit induced system susceptibility to the radiation environments. This analysis is normally performed at the system radiation specification level, for each specified radiation environment. There can be different levels of complexity of worst case circuit analysis, depending on the system requirements and the analytical ability to model the circuits and component pieceparts. Often, the radiation induced difference or delta value (that is, the device radiation induced value minus the initial value) is used rather than the absolute values in order to relate change values to other devices of the same type. Worst-case circuit analysis requires a knowledge of the: (1) circuit functional and operational requirements, (2) device types to be used and the manufacturers electrical specification limits, (3) radiation sensitive parameters and their response as a function of radiation, (4) radiation response of the surrounding, connected parts, (5) temperature derating, 6) annealing, and (7) possible aging factors. With these inputs, under the worst-case circuit operating conditions (frequency, bias, temperature, etc.), a maximum or minimum end-point electrical-parameter failure value, PAR_{FAIL} is determined; this value is taken as the circuit failure value for the device and parameter under evaluation. Whether PAR_{FAIL} is an upper value or a lower value should be indicated. It should be noted that PAR_{FAIL} may also be the result of abrupt functional failure.

5.1.4.1 Parameters of interest. Often, only one or two electrical parameters are of primary interest for each radiation sensitive device type (e.g., gain and/or fan-out for bipolar devices and functional failure and/or delay time for MOS ICs). In addition to these primary parameters, other parameters (e.g., response time) could be critical for particular device applications. These special parameters may or may not be especially radiation sensitive, and each case must be evaluated individually. It should be noted that for a particular device type, 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 PAR_{FAIL} value should be used for a given part type.

5.1.5 Limited-worst-case circuit analysis. In many cases, a Limited-Worst-Case (LWC) assessment may be appropriate. If all failure budget allocation parameters associated with a full reliability program are taken into account, the result may be an unaffordable HA program. Reliability variables (considering HA a subset of reliability for nuclear survivable systems) include: temperature effects over the military operating range; neutron short-term annealing; TDE; aging, synergism of gamma and neutron effects and allowable piecepart statistical failure rate related to system total piecepart count. Many of these variables are not established or fully understood. Factors based on engineering judgement to account for these variables may be applied for a limited-worst-case analysis though the applicability and accuracy of these factors may be subject to question.

5.1.6 Circuit hardening. Hardening through circuit design can be a 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. Circuit design should minimize the sensitivity of critical parameters, e.g., transistors should be operated in the region of collector current values that maximize gain, and avoid operation at very low or very high current levels.

b. Applied operating voltages, biases and current limiting should be in keeping with the combined ionizing dose and neutron degraded parameters as well as with any other radiation requirements such as dose rate and single event upset.

c. Device derating should be applied. That is, devices should not be operated at their limits but at some percentage or factor below either their nominal or limit values. For example, transistors may be operated at 80 percent of nominal output drive current and logic circuits at 80 percent of fan-out capabilities. Derating for radiation effects should be coordinated with other reliability derating factors to prevent excessive derating.

d. Circuits should be designed to maximize the use of less-sensitive parts. For example, to reduce susceptibility with respect to ionizing dose damage, bipolar digital logic devices may in some cases be used instead of CMOS logic, provided of course that power requirements and other design constraints permit.

5.1.7 Piecepart selection. One of the more cost-effective steps in a piecepart HA program is the selection of radiation-tolerant pieceparts. Because there are as yet no reliable electrical correlations for predicting the radiation sensitivity of electronic pieceparts in an ionizing dose environment, the main reliance for HA must be placed on adequate qualification testing with parts procurement specifications in keeping with the determined design margins. Some initial decisions can be made based on technology or accumulated historical data. For instance, bipolar devices are generally much less susceptible to ionizing dose than are MOSFET devices. However, for state-of-the-art microcircuits, ionizing dose effects can be significant in both CMOS and advanced bipolar devices. Both CMOS and bipolar families have wide ranges of specific part radiation response and radiation characterization data is necessary to assure device acceptability.

5.1.7.1 Neutron environment. Piecepart selection for the neutron environment is somewhat better understood than it is for ionizing dose, though a test data base here is also essential. Probably the most important consideration is that the individual transistor gain-bandwidth product be as high as practicable with consideration of the device power requirements. It has been shown that the incurred neutron damage is inversely proportional to the gain-bandwidth product (see 6.20). Also, the transistor should be operated near the peak of the gain versus collector current curve in order to minimize damage effects.

5.1.7.2 Use of data banks. For both ionizing dose and neutron effects, historical data in data banks may provide adequate design information for initial parts selection.* In some cases, where the data are current, are of high quality and are for identical parts, it can be acceptable for parts qualification. Lot acceptance testing will be necessary for parts with small design margins and periodic sample testing should be performed even on parts with relatively large design margins. Information relating to piecepart selection can be found in section 6.5 through 6.9 herein and in numerous other Government and contractor developed documents.

5.1.7.3 Variations between device manufacturers. Device manufacturer selection can be very important to piecepart selection for radiation environments. Radiation test results indicate that certain device manufacturers produce particular piecepart types that are harder than those of other device manufacturers for the identical part type. For example, if the results of a radiation test indicate that a certain device manufacturer's transistor has a large design margin, it cannot be assumed that the same

* The Government-sponsored radiation effects data bank, ERRIC, is maintained by DASIAC, Kaman Tempo, Santa Barbara, CA, telephone (805) 963-6484.

transistor type from a different device manufacturer will have a similar, large design margin. This means that in many cases, a device manufacturer must be considered as sole-source for procurement purposes, unless additional device manufacturers can be qualified. It is important to note that, because radiation sensitivity is highly process-dependent, even a qualified device manufacturer's line may change with time with possible adverse effects on the radiation response. This is why it is recommended that occasional sample testing be performed even on parts which have been qualified with relatively large design margins.

5.1.7.4 Radiation hardness assured (RHA) devices. Qualification and control procedures have been developed for piecepart types to be accepted as RHA devices. The incorporation of qualified standard parts such as Q and K (QML), J(JAN) RHA and Standardized Military Drawing (SMD) RHA pieceparts (6.25) is the result of efforts of the DNA Hardness Assurance Program and the NASA/AF-SMC Space Parts Working Group (SPWG) in conjunction with the Defense Electronics Supply Center (DESC) to make available military qualified, RHA pieceparts on an off-the-shelf basis. The ability to procure standard RHA qualified pieceparts without a particular system having to qualify them should significantly reduce both the cost and complexity of designing and building radiation hardened systems. Pieceparts procured as standard RHA devices should be accepted for use in hardened systems without further qualification or lot acceptance testing if the piecepart assured radiation hardness level (table I) meets the system radiation specifications.

5.1.7.4.1 Non-JAN parts. The term "RHA" is also used by some device manufacturers to identify pieceparts which have been produced to other requirements (e.g., 883 compliant devices) and whose radiation response has been characterized. However, the RHA pieceparts addressed here are restricted to standard military certified RHA devices where Government auditing of the manufacturing processes are imposed. Care must be taken by contractors to be certain that their procured RHA pieceparts are indeed acceptable for the military application.

5.1.7.4.2 RHA designators. MIL-H-38534, MIL-I-38535, and MIL-S-19500 present the four sets of radiation levels to which standard RHA devices are assured to be hard, the part numbering (designator) system and the applicable qualification procedures. RHA levels and designators are given in table I.

5.1.7.4.3 Standardized RHA part marking. Standardized military microcircuits are divided into commodity or reliability classes built to MIL-H-38534 class H (std) and class K (std. space), MIL-I-38535 classes Q, B (std.) and classes V, S (std. space) and MIL-STD-883, section 121 compliant class M. The designator for a particular RHA microcircuit is included within the device specification number. If a slash (/) or a dash (-) occurs in the number, it is not an RHA piecepart. If an M, D. R or H occurs in place of the slash or the dash, it is an RHA microcircuit in accordance with the radiation levels in table I. For example, Q38510/29101BCX is not an RHA device while Q38510R29101BCX is the RHA equivalent microcircuit assured to be hard to the R level. Another example when using an SMD, Q5962-3829401VCX is not an RHA device while Q5962R3829401VCX is a RHA assured device. MIL-S-19500 (JAN) semiconductors are divided into four product assurance levels JAN, JANTX, JANTXV, and JANS. JAN and JANTX are not recommended for use as RHA specified pieceparts, while JANTXV and JANS are the preferred product assurance levels for use as RHA pieceparts and will be indicated by the appropriate letter designator appearing as a suffix to the JANTXV or JANS indicator, i.e., JANTXVR 2N7291 or JANS 2N7291 for an RHA level R piecepart.

TABLE I. Radiation hardness assurance levels.

RHA level designator	Ionizing dose (rads(Si))
/	No RHA
M	$3X10^3$
D	10^4
L	$5X10^4$
R	10^5
G	$3X10^5$
F	$6X10^5$
H	10^6

5.1.7.4.4 RHA device substitution. RHA devices assured to higher radiation levels can be used in place of lower assured levels when pieceparts specified for the lower level are not available. For example, an R device can be used in an M application without further qualification. Devices who's response is not monotonic with dose are dealt with at DESC by adjusting the post-irradiation specification limits to the worst case value.

5.1.7.4.5 Additional qualification. In addition, a standard RHA device specification may serve as a starting point where unique system requirements differ from or exceed the given RHA certified level through further radiation qualification of each device type by the contractor. The rationale here is that the RHA device manufacturers are aware of the potential radiation response dependence on processing stability. This provides a degree of parts stability related to unique hardness considerations from which to baseline further qualification and controls for hardness.

5.1.7.5 Standard/nonstandard pieceparts. The recommended hardening and HA programs are structured around the use of standardized military devices. This provides Government cognizance (through auditing) of manufacturing processes and stability at a minimal cost to the system since it is already in place for cost effective reliability purposes. Standard parts for application of this handbook are devices built to Military Specifications (slash sheets) and SMDs, either QPL or QML. The difference between standard and nonstandard parts for these HA control applications is in the need for unique line qualification and production lot acceptance testing for nonstandard parts (section 5.4.3.3).

5.1.7.5.1 Preferred devices. Microcircuit parts selection should be in accordance with Requirement 64 of MIL-STD-454 (Standard General Requirements for Electronic Equipment - 6.21) and MIL-STD-1562 (Lists of Standard Microcircuits - 6.22) which require the use of standardized military parts as first choice. When needed part types are not available as a standardized military part, nonstandard parts may be used subject to the procuring activity approval.

5.1.7.5.2 Class M parts. Class M pieceparts are procured in accordance with the guidelines specified in MIL-HDBK-780. Class M pieceparts are listed in MIL-BUL-103, and are subject to random periodic production line validation by the DESC auditing system.

5.1.7.5.3 883-compliant devices. Though not addressed in MIL-STD-454, MIL-STD-883 compliant devices may be considered acceptable for use in radiation hardened systems with the approval of the procuring activity. This approach would be most applicable to systems with low level requirements where relatively large DMs can typically be achieved. 883-compliant devices are produced in accordance with section 1.2.1 of MIL-STD-883, essentially as high reliability devices. The Government does not necessarily monitor or have any control over 883-compliant production lines which would effect the radiation response. These devices are not permitted to display the QML or JAN marking. It should be noted however, that acceptance of these as standard may conflict with the systems HA program requirements for parts tracking. The general HA program may specify that if a standard part is not available a procurement drawing must be developed that includes all the information necessary for procurement of that part. These drawings may take the form of source or Specification Control Drawings ((SCDs) or vendor item description) or selected item drawings (SIDs). Thus, in effect the 883-compliant device becomes a de facto nonstandard part since a procurement drawing is necessary to acquire it.

5.1.7.5.4 Standard part listings. The standard military part listings for DESC certified devices are as follows:

a.	MIL-BUL-103	Device class M (MIL-STD-883 compliant microcircuits)
b.	QML 38534	Device classes H and K (hybrid microcircuits and MCMs)
c.	QML 38535	Device classes Q, B, S, and V (monolithic microcircuits)
d.	QPL 19500	Device classes JAN, JANTX, JANTXV, and JANS (discrete semiconductors)

5.1.7.5.5 Commercial parts. Sometimes, of necessity, commercial pieceparts will have to be used in a system. These must certainly be considered nonstandard, and adequate qualification and periodic procurement testing as related to the design margin must be performed. Since such parts are not subject to military specification production controls, larger variations in radiation response should be expected. Hence more attention must be paid to the make-up of the characterization sample lot and to the minimum acceptable DM.

5.1.8 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 to accommodate the available margin, (3) localized radiation shielding may be added, particularly for ionizing dose in space applications, or (4) the unirradiated remainder of the lot may be electrically screened to tighten the population distribution following which, radiation sample testing may again be performed. In many cases, a screening procedure may be unknown, impractical or too difficult and expensive to implement. Many of these problems are related to the lack of electrical screening parameter correlation with ionizing radiation damage.

5.1.8.1 Piecepart substitution. As previously explained, there can be a significant variability in radiation sensitivity between different manufacturers and part types. Consequently, a design hardening technique to upgrade an unacceptable or small DM part is to use the same part type from a different manufacturer or make use of a different, harder part type. This is a cost-effective method of improving the radiation hardness of the circuit. However, the substitute part type must be fully evaluated by characterization testing prior to being used.

5.1.9 Unacceptable pieceparts. Part types with small design margins should be eliminated from use in the system. By definition, parts with a DM equal to one have only a 50 percent probability of survival. Part types with a design margin between one and three have a high probability of either lot rejection during lot acceptance testing or radiation induced circuit failure and hence should not be used. For a piecepart with a small design margin, the decision on acceptability will depend on the cost of rejecting production lots versus the cost of either using a harder part type or redesigning the circuit. Since these costs are highly dependent on the specific part type and the system in which it is used, no one formula for determining a minimum acceptable design margin can be optimal for all situations. Recommended general rules are:

a. Part types with design margins of one or less cannot be used since this means that the equipment will not meet the nuclear specifications.

b. The minimum acceptable design margin should be two to three, with devices accepted below this level only after all potential substitute (replacement) parts have been eliminated and all reasonable circuit design changes to alleviate the problem have been examined.

5.1.9.1 Minimum DM. As a matter of practicality, this value of two to three may be tempered for very high dose or fluence levels. For example, a factor of three on a 3 krad specification results in a 9 krad requirement, and is likely achievable. On the other hand, a factor of three on a 1 Mrad specification results in a 3 Mrad part requirement, which may not be achievable. However, if the minimum design margin is reduced, adequate sample sizes and controls must be applied to assure the part's survivability. Note that this minimum DM is not applicable to RHA devices. If an RHA device radiation specification meets or exceeds the system requirements, further DM considerations are unnecessary; they have already been included in the RHA level.

5.1.10 Radiation shielding. For most space based systems, and some high altitude aeronautical systems, shielding may be incorporated to reduce x-ray and space borne particulate radiation incident at the pieceparts. Shielding against nuclear weapon produced gamma and neutron radiation is typically impractical for these systems. By adding localized radiation shielding around a part, the ionizing dose radiation level may (particularly in space radiation cases) be reduced sufficiently to allow use of a marginal part type, depending on the part sensitivity and the radiation type and energy spectrum. For fixed-site ground based systems, where large volumes of dense materials may be employed, shielding against weapon radiation may be practical. Adding localized shielding can be a cost-effective way to harden a system, particularly when only a few radiation sensitive part types are involved, provided the system design limits can tolerate the additional weight and volume of the shielding material and it can be reasonably incorporated.

5.1.10.1 Spacecraft shielding. In spacecraft systems, the radiation level at the electronic pieceparts is often lower than the system ionizing dose specification because of the shielding provided to the circuit by the box in which it resides and other surrounding materials. In such cases, the radiation level may be calculated based on the materials' absorption. But because of their complexity, such calculations are usually done on a computer by knowledgeable people using appropriate transport codes. The piecepart package itself (where the material and configuration are usually known) provides a very large attenuation to electrons and low energy x-rays. If detailed information about the surrounding masses is not known, then a typical limited-worst-case procedure might assume 40 mils of aluminum shielding to account for the electronics box and some system outer skin shielding. Since existing self shielding to x-rays and low energy particulate radiation is quite often substantial, a calculation of the resultant shielded dose at the electronics should be mandatory for a cost effective program.

5.2 Hardness assurance, maintenance and surveillance. In order to assure system lifecycle survivability, three fundamental programs must be applied: Hardness Assurance (HA), Hardness Maintenance (HM) and Hardness Surveillance (HS). This document primarily addresses HA at the pieceparts level, though some descriptive information is included where necessary to relate the piecepart information to systems level HA, HM, and HS.

5.2.1 HA general requirements. The HA program is developed during the Research, Development, Test & Evaluation (RDT&E) phase, and applied during production to assure that the production line products are in conformance with both the nuclear weapon effects specifications and the final, accepted design. The HA program is comprised of all steps necessary to assure that the system meets all technical, managerial and documentation requirements. HA is much the same as quality control for specific effects, and may be considered a subset of the normal production quality control.

5.2.1.1 HA general controls. In order to assure production equipment hardness, controls must be applied from the systems level down to the individual piecepart level. Through actions of the Configuration Control Board (CCB, MIL-STD-480) and the Parts Control Board (PCB, MIL-STD-965), procurement of qualified pieceparts and their proper application in the system are controlled. In addition, any special assembly procedures or test requirements to be applied during production must be specified. All pieceparts procurement problems, piecepart substitution or design changes made during production must be cleared through the CCB and the PCB and the nuclear Survivability/Vulnerability (S/V) personnel assigned to these boards. All changes should be reviewed by S/V personnel since relatively innocuous changes from other engineering standpoints may be significant from a nuclear S/V aspect. All HCI design changes or substitutions and HCP assembly-procedure changes must be monitored and recorded for traceability. The prime vehicle for baselining the control and traceability requirements is the Hardness Assurance Design Documentation or the Nuclear Survivability Design Parameters Report (see 6.35). In addition, for system's control of pieceparts, Hardness Critical Items (HCIs) requiring special S/V attention have been defined and appropriate drawing markings specified in MIL-STD-100, Engineering drawing Practices (see 6.24).

5.2.1.2 HA piecepart controls. All radiation sensitive pieceparts (primarily semiconductors) used in the system must be controlled to some degree. Controls, as used here, refer to any requirements beyond those normally applied to the procurement of MIL-STD parts. Procurement controls include such things as specifying: acceptable parameter screening limits, sole source restrictions, manufacturer's radiation testing, and special manufacturing process controls including controlled or captive lines and radiation related test structures (see 6.23). In addition, radiation related lot acceptance testing (usually performed by the contractor) constitutes a control. The primary means of semiconductor piecepart procurement control is with use of SOCDs, vendor item drawings or SIDs as defined in MIL-STD-100 (see 6.24) or SMDs as defined in MIL-HDBK-780 (see 6.25). Special parts, materials and process control procedures for space and launch vehicles are addressed in MIL-STDs 1546A and 1547A (see 6.26 and 6.27). Guidelines addressing the controlled procurement of custom large scale integrated circuits are given in MIL-HDBK-339 (see 6.28) and in 6.29 herein.

5.2.1.2.1 HCC-1M controls. The level of control for each piecepart type is related to the design margin and Hardness Critical Category (HCC). The more sensitive pieceparts (HCC-1M) require the greatest control and must have part level engineering drawings to assure procurement of qualified pieceparts. These drawings are developed from the piecepart qualification program data and must include all information necessary to the procurement of acceptable pieceparts. This information incudes any processing, traceability or test requirements levied on the manufacturer. Since these sensitive pieceparts require lot acceptance testing, the details of the lot acceptance testing procedures and the acceptance/rejection criteria must be included in the production piecepart procurement drawing.

5.2.1.2.2 HCC-2 and HNC controls. The less sensitive (HCC-2 and hardness noncritical, HNC) pieceparts have as a primary control the requirement that they be MIL-STD or SMD (or possibly system approved MIL-STD-883 compliant) devices. Though the procurement requirements are identical for HCC-2 and HNC, there are differences in qualification sample sizes and periodic requalification requirements (see 5.4.3.1.3). The procurement drawing for these less sensitive pieceparts should provide only the MIL-STD or SMD part number or approved manufacturer(s) of the equivalent 883 compliant piecepart.

5.2.2 Hardness maintenance (HM) and hardness surveillance (HS). HM and HS are applied throughout the system's operational lifetime and will only be briefly touched on here. HM consists of those S/V related procedures necessary to ensure that the system hardness is not degraded through normal operational or maintenance procedures over the life of the system. HS consists of the tests and inspections that are necessary to verify the system hardness and the effectiveness and adequacy of the HM program. Though the HM and HS procedures are the responsibility of the appropriate military service logistics organization, they must be developed by the contractor in coordination with the SPO or PEO and the responsible logistics organization. The HM and HS program documentation must be deliverable Data Items (DIs) with delivery schedules in keeping with the first delivered hardware item, and with possible updated DIs during and at the end of production, depending on production duration.

5.2.3 HA design documentation (HADD). Documentation of the design hardening approach, final hardened design, HA procedures, parts selection, parts procurement specifications, hardness dedicated parts, circuits, etc., is an important aspect of the HA program (see 6.30 through 6.32). HADD is the term developed by the Air Force for the organization of the documents which provide a cost-effective means of assuring proper control of hardened equipment during both production and deployment. The design hardening and HA associated information should be deliverable items in every development contract. The Army has developed Data Item Descriptions (DIDs) associated with system hardening and HA (see 6.33 through 6.38). Design, hardening procedures and parts data may be in the form of well organized, readable, handwritten engineering notes and drawings or as more formal documents including other required reports such as vulnerability assessment reports. The HADD serves as the basis for configuration and parts control throughout the system lifecycle. Though the HADD requirements may seem extensive, the information is essential for traceability relating to both the baseline design and design changes or piecepart substitutions occurring throughout the production and deployment phases. The HADD must be coordinated for approval with the SPO or PEO and the contractor's Quality Assurance (QA) and configuration control organizations.

5.2.3.1 Required piecepart information. The following items outline the piecepart information appropriate to either qualification or lot acceptance as applicable but should not be considered all inclusive:

a. Reference to the radiation environment specifications and survival requirements.

b. Part type, vendor and wafer/inspection traceability.

c. Critical parameters and predicted radiation response.

d. Bias conditions during irradiation.

e. Operating conditions during electrical measurements.

f. Measurements in-flux, in-situ, or remote.

g. Test setup and measurement equipment.

h. Radiation levels and deposition rates.

i. Radiation levels for parameter measurements.

j. Dosimetry type, application and read-out.

k. Time between irradiation and measurements.

l. Critical parameter(s), nominal and failure level(s).

m. Pertinent statistical values associated with the piecepart.

n. Applicable sample and acceptance criteria or criterion.

o. Recommended additional periodic sample testing.

p. Other data or information relevant to future procurement.

5.2.3.2 HCI information. In addition, a Hardness Critical Item (HCI) list (6.35) shall be delivered which provides the procurement document (drawing or specification) citation for each HCI and a cross index to the specific volume, chapter and section of the Nuclear Survivability Design Parameters Report or other delivered document. The HCI definition and drawing marking requirements are specified in MIL-STD-100. MIL-STD-100 also requires drawing notes with the HCIs and HCPs which reference documents which provide the basis for the HCI or HCP (6.24). The purpose of these notes is to reference the Nuclear Survivability Design Parameters Report (6.35) or other appropriate, delivered reports so that in the future, if a part is no longer available, the basic design information can be located which will enable the proper redesign or choice of alternate parts or circuits. Also, the specialized note in section 501.4.1 of MIL-STD-100E should provide the name of the engineering activity responsible for evaluating changes to the equipment's HCIs or HCPs.

5.2.4 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. Cost trade study efforts must be made to minimize 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 avoids future lot acceptance testing. Each part type, vendor selection, circuit design, and application should be evaluated regarding the effect it has on both the costs and risks of the production and maintenance phases of the program.

5.3 Radiation response measurements. Semiconductor piecepart parameter measurements are of fundamental importance to both design hardening and the ensuing HA programs.* These measurements may include both static and dynamic parameter characterizations for both preirradiation values and device response to radiation. Information provided in this section addresses: 1) the data base requirements, and the relationship of existing and newly developed data; 2) characterization measurements for basic design considerations; 3) the two basic measurement techniques, attributes and variables; 4) and a presentation of lognormal statistics applicable to the described HA programs.

* MIL-HDBK-816, "Guidelines for Developing Radiation Hardness Assured Device Specifications" is a related reference. Increased survival and confidence requirements also necessitate a better data base, which may be achieved primarily through an increased sample size. Another (nontechnical) driver of some consequence is cost: both test parts and testing are expensive. (A technical aspect of the costs is the complexity of the test requirements for a given device. That is, the number of initial conditions and timing requirements relate to the testing time and the test equipment needed.) Currently, the costs of many integrated circuits make it unfeasible to test a statistically satisfactory sample: this then becomes a "work-around" problem to reach a solution that is satisfactory to the concerned parties, particularly the SPO or PEO.

5.3.1 Data base. In order to make engineering evaluations of piecepart response to the radiation environments, adequate existing data must be found, or new data developed through a test program. Data adequacy, whether existing or new, must be determined through engineering judgement based on numerous factors related to the particular system of concern. A major point is the radiation stress level specified. If the stress level is quite low and the part technology well understood, the data base requirements need not be stringent. On the other hand, if the stress level is severe, the data base may need to be extensive for adequate part characterization. Of equal consideration with the stress level are the probability of survival and confidence imposed at the system and ultimately at the piecepart level.

5.3.1.1 Use of existing data. In order for existing data to be acceptable for characterizing a device, an engineering evaluation should be made of the data against the following minimum requirements:

a. The part type, vendor and bias conditions during radiation testing and parametric measurements should be approximately the same as those used in the circuit analysis.

b. The radiation test environment at which the data were taken should be acceptably close to the environment given as the system requirement.

c. The data should be in a format that permits evaluation of parameter changes as a function of the radiation level at a minimum of three radiation levels.

d. The highest radiation level for the test data should be at least twice the system's specification to allow verification that the part behavior is not beginning to change rapidly just above the specification level.

e. The data should provide information on parameter measurement time with respect to the time of radiation exposure.

f. The data should preferably be of recent origin in order to increase the likelihood that the devices tested are representative of currently produced devices. Note that device manufacturing processes can change at any time and that even recent data may not be truly representative of current production devices.

5.3.1.2 Limited use. If the above conditions cannot be met, the existing data should not be utilized or incorporated with new data to demonstrate device qualification to the system specifications. However, such data may be used where practicable to promote insight into anticipated device response, and for initial design hardening studies.

5.3.2 Measurements. Typically, applied radiation testing falls under one of two basic procedures, testing by variables (see 6.39) or testing by attributes (see 6.40). Characterization testing is usually an application of the variables method to develop radiation response data over a range of applied radiation stress. Variables data is especially applicable to both design hardening and piecepart qualification. Radiation characterization data for application early in the design phase may be derived in large part from existing data bases. As more definitive data are required for final design and qualification, existing data may be augmented or replaced by further characterization testing. Data should be sampled from several lots produced over a significant span of time, but of as recent origin as practicable to assure acceptable multi-lot variability. Attributes testing is usually accomplished through a single radiation exposure of a test sample with electrical test criteria applied for lot acceptance or rejection. Attributes testing is most applicable to lot acceptance testing where full characterization of the part type is not required.

5.3.2.1 Statistical sampling. It is important to note that the variables and attributes methods are tests which reject unsatisfactory lots on a statistical basis. They do not necessarily guarantee that accepted parts will work with the given confidence and probability. The importance of this point is that lot acceptance histories and past experience provide essential information. A poor past performance indicates a poor part in spite of its passing a test. On the other hand, a good past performance can indicate a strong likelihood that the desired survivability and confidence will be met. These conclusions are related to reasonably normal line stability: if manufacturing processes are changed, significant changes in the radiation response will often occur.

5.3.2.2 Extrapolation. Small sample characterization data should not be used to extrapolate survival probabilities to high confidence levels. Such an extrapolation requires an appropriately large sample size and a more exacting consideration of the distribution by means of a statistical test such as the Chi-square goodness-of-fit or other standard statistical test (reference 6.41). (It should be kept in mind that a minimum sample of 25 is required for the Chi-square goodness-of-fit which can be used as a test for normality.) If the true population deviates from the assumed distribution based on small sample data, large errors may be encountered, particularly for high survival requirements (e.g., P_S equal to or greater than 0.999).

5.3.2.3 Testing by variables. Variables testing generally refers to test procedures whereby incremental piecepart electrical measurements are made either at points in time while being irradiated or at step levels (step-stress) between increments of radiation (see appendix A, 50.3). Thus, tabular or graphical characterization information is obtained which can give a continuous interpretation of the part's radiation response. This method is most applicable where the response or degradation is a continuous function of the accumulated radiation (i.e., graceful degradation). From this, one can determine the statistical behavior of a variable (for example, fluence to failure or PAR_{RAD}) under test conditions. This method has the advantage of being able to predict a low failure probability, with high confidence, on the basis of a relatively small sample size. It has the disadvantage that it requires assumptions about the probability distribution of the variable involved. However, such assumptions are often acceptable since the advantage of being able to use sample sizes that are reasonably attainable can far outweigh the disadvantages.

5.3.2.3.1 Abrupt failure. If abrupt failure occurs between unacceptably wide stress measurement points, further stress testing of a new sample should be performed with smaller stress increments to adequately bracket the region of abrupt failure. An alternate method for analytically estimating parameter end-points for devices that suffer abrupt functional failure is provided in 6.15.

5.3.2.4 Testing by attributes. Attributes testing is a method by which a test sample of pieceparts is typically exposed at a single radiation level and evaluated against a pass/fail criterion derived from the qualification test data (see appendix A, 50.3.1). (Iterative testing may also be performed at increasing exposure levels to determine the sample failure threshold based on the pass/fail criterion.) The procedures for a Government accepted attributes method and appropriate tables are presented in appendix B of MIL-I-38535, appendix A and more fully in MIL-STD-105. Application of the method involves testing of the sample at a given radiation level and comparing the data with a predetermined parameter failure level. In the typical radiation test application, where the minimum sample size is selected, the test data must show no failures: if a single failure is observed, the lot must be rejected or an additional sample may be chosen as specified in MIL-I-38535, appendix B and qualified in accordance with table B-1. (For RHA ICs, see MIL-STD-883, method 5005, group E tests.) Alternate sample sizes with other allowable failure rates may also be selected though the sample size becomes quickly prohibitive. This method has the advantages that the distribution need not be known for either the parent population or the sample, and that test data need not be analyzed beyond relating it to the pass/fail criterion. It has the disadvantage of requiring a relatively large sample size.

5.3.3 Lognormal statistics. In some naturally occurring phenomena, the frequency plot is noticeably skewed to the right rather than being representative of the symmetrical normal distribution plot: these data may be handled with use of lognormal statistics. The majority of semiconductor piecepart radiation test data is best represented by the lognormal distribution. Where the data do not conform to the lognormal distribution, an alternate (e.g., normal), appropriate distribution should be assumed and applied in a manner analogous to that described for the lognormal distribution. Some detail for the normal and lognormal distributions may be found in the appendix.

CAUTION

Note that the argument of a logarithm must be a pure number. It should be understood that the argument has been made dimensionless (normalized) by dividing it by a unit quantity having a value of one but with the same dimensions as the variable in question. That is, a parameter value such as dose expressed in rads(Si) must be divided by 1 rad(Si) in order to be dimensionless prior to taking the logarithm. In addition, following the logarithmic manipulations, the anti-log is taken to return to "normal-space", and a denormalizing factor (the inverse of the applied normalizing unit quantity) must be applied to the anti-log derived value in order to return the value to proper dimensions. These normalizing/denormalizing functions may be performed implicitly or explicitly, but are necessary since dimensions carried into "log-space" may be returned to normal space in an indeterminate state when taking the anti-log.

Note also that, in order to keep the equations as readable as possible, these normalizing/denormalizing factors are not explicitly shown in the following presentation of lognormal statistics or in the examples shown later.

In addition, it is essential that the dimensions (units) of the electrical parameter and radiation values applied to the equations be consistent throughout each application. That is, for example, if the radiation level is expressed in rads in one portion of an equation, rads must be used for radiation levels throughout the equation: ionizing dose dimensions may be in terms of either rads or grays, but must not be mixed in a computation.

5.3.3.1 Lognormal statistics. For lognormal statistics, the mean usually refers to the geometric mean and the variance of the data to the geometric dispersion. In lognormal statistics, the logarithms of the data point values are normally distributed. In order to apply normal statistical calculations to lognormal data, it is first necessary to transform the data into a normal distribution by taking the logarithms of the data values. When these log-values are plotted on normal-probability paper (figure 3, also see appendix 50.2.1.4), they should, within visual standards, fall about a straight line. (The data from which this probability plot was derived are given in table VI.) Normal statistical calculations are performed on the log values, following which the antilogy must be used to transform the calculations back into the lognormal form. Though the lognormal equations appear somewhat more formidable than the normal equations, operationally, it is a matter of taking the log values of the parameters, performing the functions and then taking the antilogy to return to real space. The generalized lognormal equations for parameter (x) and sample size n are presented below for determination of the mean and standard deviation.

lognormal mean

$$\overline{\ln(x)} = \frac{1}{n}\sum_{i=1}^{n} \ln(x_i) \qquad \text{Eq. 5.3.3-1}$$

lognormal standard deviation

$$s_{\ln(x)} = \left(\frac{1}{n-1}\sum_{i=1}^{n} [\ln(x_i) - \overline{\ln(x)}]^2\right)^{1/2} \qquad \text{Eq. 5.3.3-2}$$

The geometric mean value of (x) is given by the antifunction xM and the geometric standard deviation is given by the antifunction of the

$$xM = e^{\overline{\ln(x)}}$$ Eq. 5.3.3-3

lognormal standard deviation

$$x = e^{[s_{\ln(x)}]}$$ Eq. 5.3.3-4

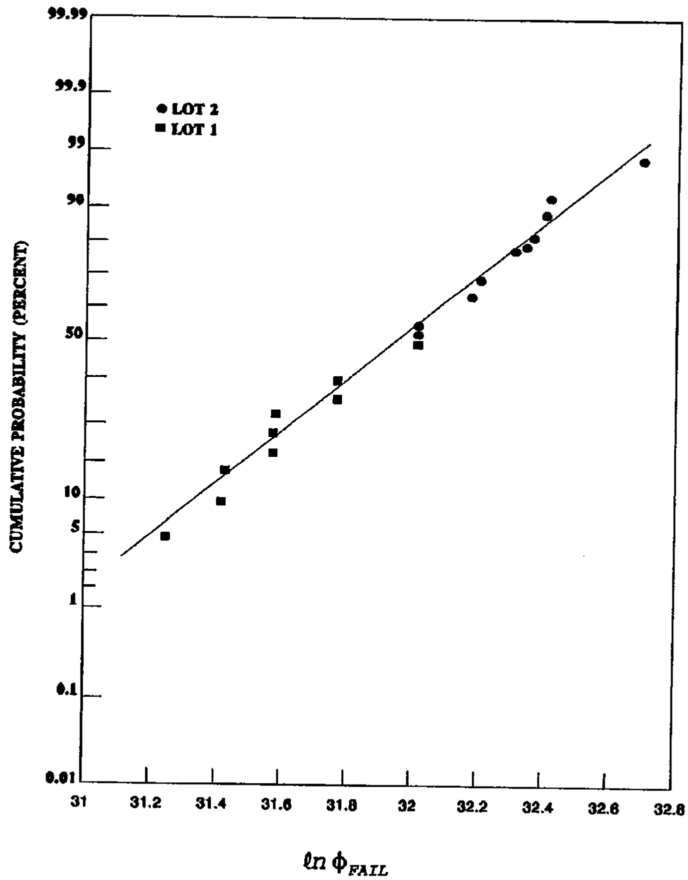


FIGURE 3. Cumulative plot on normal probability paper. Logarithms of neutron fluence-to-failure of 20 2N2222 transistors drawn from two lots.

5.4 Design margins and hardness critical categories. This section presents the detailed procedures for the determination of piecepart Radiation Design Margins (RDMs) and Parameter Design Margins (PDMs), and provides the definitions of the Hardness Critical Categories (HCCs). Determination of the RDM or PDM is identical for either the DMBP or PCC method. Piecepart categories determined by either method are in keeping with the definitions in this section. Note that the DM criteria do not have to be considered for RHA pieceparts. If the RHA radiation level and survivability for a particular piecepart meets or exceeds the system requirements, it should be directly usable without further DM considerations. The described methods present the case for the lognormal distribution. However, if the data are normally distributed, the standard normal equations for the arithmetic mean and standard deviation should be applied to the data values rather than the logarithms of the data values. If the distribution is other than normal or lognormal, an alternate, appropriate distribution may be assumed and applied in a similar manner (appendix, 50.2.3).

5.4.1 Managing HCCs. HCCs are useful tools to segregate pieceparts according to their design margins. Once this segregation is made, the testing requirements and the level of control for procurement of the part and equipment are determined. However, drawings and lists associated with an equipment do not recognize HCCs (MIL-STD-100). What is needed for the equipment technical data package is the basic information on how to procure these pieceparts with the features the designer intended and how to insure that when change proposals are submitted against these "special" parts, that these parts are clearly indicated as being critical to the equipment's nuclear hardening.

5.4.1.1 HCI and HCP notation. In recognition of these needs, two markings for drawings and their associated lists were chosen: Hardness Critical Item (HCI) and Hardness Critical Process (HCP). HCI refers to a piecepart, material or software that is some way critical to an equipment nuclear hardening; HCPs are required for the manufacture or repair of an item or assembly which insures that the nuclear hardness is maintained (see MIL-STD-100 for complete definition). The Engineering Drawing Practices standard (MIL-STD-100) requires that the HCI and HCP markings shall be used on all the appropriate drawings and lists where an HCI or HCP is found, including the higher level assembly drawings. Moreover, there is a note by the title block to call attention to the fact that HCIs and/or HCPs are found on that drawing or list and that changes shall not be made without the appropriate engineering activity being consulted.

5.4.1.2 Design disclosure information. Additionally, there is a requirement that the drawing or specification for that HCI "provide the design disclosure information necessary to enable a manufacturer of similar products at the same or similar state of the art to produce and maintain quality control of items so that the resulting physical and performance characteristics duplicate those of the original design".

5.4.2 Design margins. DMs are values which may be expressed in terms of either radiation or electrical parameter ratios. Most frequently used is the Radiation Design Margin (RDM) which is expressed as the mean radiation level at which the test sample of parts reaches a predetermined (functional or parameter) failure level (PAR_{FAIL}), divided by the radiation specification level. The Parameter Design Margin (PDM) is determined by taking the mean of the (critical) parameter value at the radiation specification level and dividing it by the predetermined circuit failure value for that parameter, PAR_{FAIL}. The value of PAR_{FAIL} for every critical electrical parameter for every semiconductor part in the circuit must be determined through circuit analysis.

5.4.2.1 Lognormal mean failure value. In order to calculate the RDM for lognormal statistics, it is necessary to determine the lognormal mean failure value, R_{MF}, (see equation 5.3.3-1) from the characterization test data. Figure 4 shows the case where the piecepart parametric response is an increasing function with radiation. The radiation level at which each piecepart in the sample of 5 fails (i.e., the intersection point with the analytically determined PAR_{FAIL}) is first determined. The mean failure value, R_{MF}, is then calculated using the logarithms of the individual piecepart failure values, R_{FAIL}, as follows:

$$R_{MF} = e^{\overline{\ln(R_{FAIL})}} \qquad \text{Eq. 5.4.1-1}$$

where

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

and $R_{FAIL}(i)$ is defined as the circuit failure ionizing dose or neutron fluence value for the i^{th} device in the test sample.

5.4.2.2 Radiation design margin. The RDM can then be calculated as the ratio of R_{MF} to the radiation specification value, R_{SPEC}, which the circuit must survive:

$$RDM = \frac{R_{MF}}{R_{SPEC}} \qquad \text{Eq. 5.4.1-2}$$

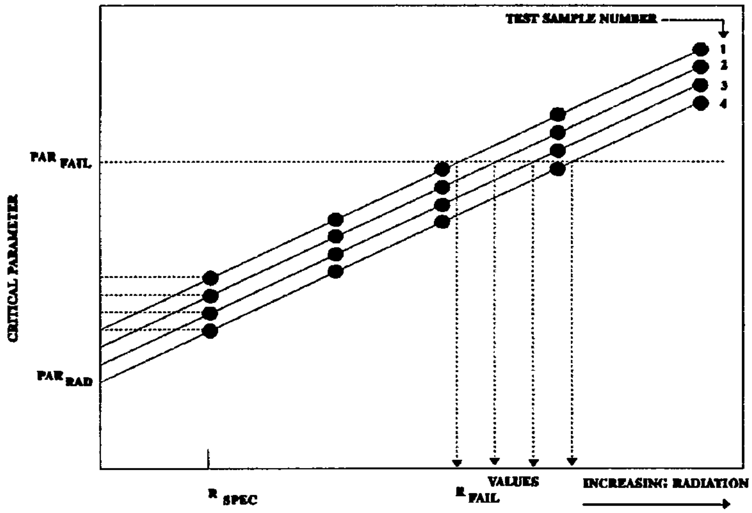


FIGURE 4. Relationship of factors used in DM determination.

5.4.2.3 Parameter values. A similar approach but based on the dispersion of piecepart parameter values at a single radiation level is also shown on figure 4. In this case, consider the radiation-induced parameter value, PAR_{RAD}, for each device taken at the specification level, R_{SPEC}. The mean parameter value, $[PAR_{RAD}]_M$ is calculated using the logarithms of the individual parameter values and taking the antilog:

$$[PAR_{RAD_M}] = e^{\overline{\ln(PAR_{RAD})}} \qquad \text{Eq. 5.4.1-3}$$

5.4.2.4 Parameter design margin. The parameter design margin, PDM, is then calculated (for the case of parameter increase with radiation) as the ratio of the PAR_{FAIL} value to the mean parameter response value:

$$PDM = \frac{PAR_{FAIL}}{[PAR_{RAD}]_M} = \frac{par_{FAIL}}{e^{[\ln(PAR_{RAD})]_M}} = \frac{PAR_{FAIL}}{e^{\overline{\ln(PAR_{RAD})}}} \qquad \text{Eq. 5.4.1-4}$$

For the case of parameter based DM computations where the parameter is a decreasing function with radiation, the above PDM ratio is inverted.

5.4.3 Hardness critical categories (HCCs). A set of HCCs has been developed based on the amount of DM achieved for each particular electronic piecepart type. The purpose of the categories is to provide guidance and consistency in the testing requirements and procurement controls applied to pieceparts procured for production systems.

5.4.3.1 HCC definitions. The five categories presented have been applied, all or in part, to a number of hardened systems. The three DM-derived categories are HCC-1M (the most sensitive based on a small DM), HCC-2 (less sensitive based on a significant DM) and HNC (insensitive based on a very large DM). There are also two categories not based on DM. HCC-1S is applied to nonstandard pieceparts and HCC-1H acts as an awareness flag for hardness dedicated pieceparts. Both part categories require the HCI marking. Additionally, HCC-1S requires a control drawing. HCC-1H parts are marked as HCIs only for the purpose of configuration control, i.e., making sure they are in all the procured and repaired equipments and that no change proposal is accepted which causes these parts to be removed from the equipment. The HCC-1H category does not require a drawing or specification for control of some specialized nuclear-effects-response parameter(s). The criteria for the determination of individual piecepart categories are presented in sections 5.5 (DMBP) and 5.6 (PCC).

5.4.3.1.1 Relationship to DM. Figure 5 is a depiction of the relationship between DMs and the breakpoint or PCC determined categories. Pieceparts having DMs falling between the minimum acceptable value of 3, for example, and the HCC-1M/HCC-2 breakpoint (or PCC) value, depending on the method being used, are HCC-1M. Pieceparts having DMs falling above the HCC-1M upper bound but below the HCC-2/HNC breakpoint are HCC-2. Pieceparts with DMs greater than the HCC-2 upper bound are HNC.

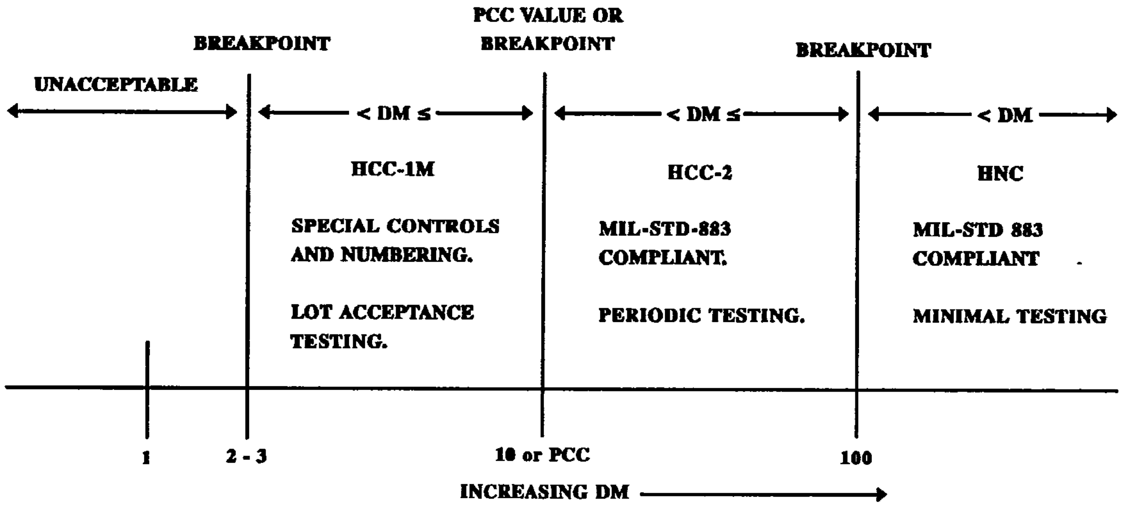


FIGURE 5. Relationship between design margin based categories.

5.4.3.1.2 Selection of breakpoints. These breakpoints are meant to be interpreted as guidelines. Careful engineering analysis could very well result in setting different breakpoints depending on the specific system requirements and specific part technologies. For example, systems with extremely high radiation requirements might be forced to use lower breakpoints buttressed by a more extensive hardness assurance program. The standard deviation of parts radiation data for MOS devices in the ionizing dose environment substantially exceeds the standard deviation for parts radiation data in the neutron environment. Thus, lower breakpoints might be useful for the neutron design and higher breakpoints might be required in some cases for the ionizing dose design. If there are a very small number of a specific device used in a system, its impact on the failure probability could be small and a lower breakpoint might be useful.

5.4.3.1.3 Procurement and test sample guidance. Table II provides summary information on procurement and testing associated with the described categories. The indicated (min, max) values in the test sample column are the minimum acceptable sample size, and if the data quality so dictates, additional samples up to the maximum sample size may be tested. Note that the maximum sample size is not an absolute maximum, but is a guideline for data evaluation. If data are taken on the noted maximum sample size and are not interpretable or inadequate in some manner, an evaluation should be made to assess the problem. Sample sizes larger than the noted maximums may certainly be used. Table II sample sizes apply to both qualification and lot acceptance testing. Additional information on sample size and test requirements is given in section 5.8.

5.4.3.2 HCC-1M. Includes all pieceparts with relatively small DMs falling in the interval between the minimum acceptable DM value of 2 to 3 and the defined HCC-1/HCC-2 breakpoint or PCC value. A minimum DM is specified since the DM is related to the statistical mean of the sample distribution and at a DM = 1, the mean-value would be equal to the specification value, and thus, approximately half of the parts would fall below the specification value and be unacceptable. As an engineering approximation, a minimum DM value of 2 to 3 is considered adequate to provide an acceptable portion of the distribution above the specification level.

5.4.3.2.1 Minimum DM. The minimum DM value, 2 to 3, should be chosen on the basis of both engineering judgement and cost-effectiveness. Higher values are more conservative, i.e., more part types will be rejected as being unacceptable. Lower values introduce more risk that some parts will be accepted which would fail at the specification level. This is particularly true for ionizing dose effects, where the variation in response is greater than that for neutron effects.

5.4.3.2.2 HCC-1M controls. All HCC-1M pieceparts must have nuclear effects procurement controls developed and fully specified in the piecepart procurement drawing. These controls must be fully adequate to assure with a high degree of probability that the procured devices will remain functional at the specified radiation levels (MIL-T-31000, General Specification for Technical Data Packages). If available as an RHA device, the drawing need only specify the RHA slash sheet number; otherwise, the procurement drawing must be in conformance with the appropriate SOCD, vendor item drawing, SID, or SMD. In addition, Lot Acceptance Testing (LAT) is required for all HCC-1M pieceparts. The contractor must develop and implement lot acceptance test procedures (see 5.8) and lot acceptance criteria (see 5.8.9). These LATs performed by the contractor are in addition to, and separate from any Quality Conformance Inspection (QCI) tests performed by the manufacturer.

TABLE II. Qualification and production procurement test sample guide.

HCC	Procure to:	Test sample min maximum #	Production parts tests
1M	RHA, SMD, SID	10 - 30	Lot acceptance
1S	SMD, SOCD	10 - 30	Periodic
1H	RHA, JAN, SMD, (883)	Margin dependent	Margin dependent
2	RHA, JAN, SMD, (883)	5 - 10	Periodic
HNC	RHA, JAN, SMD, (883)	5 - 10*	Minimal

See text, section 5.4.3
* Sample size may be reduced depending on DM and data.
RHA = Radiation Hardness Assured
SMD = Standard Military Drawing
SID = Selected Item Drawing
SOCD = Source Control Drawing
883 = MIL-STD-883 Compliant Devices

5.4.3.3 HCI-1S. These are considered second in a "control sensitivity" hierarchy. This category is applied to pieceparts considered nonstandard and are HCC-2 or HNC based on DM. Since the Government has no control or monitoring of nonstandard parts, it is necessary to provide some level of systems control even though a significant DM exists. For procurement control purposes, HCC-1S pieceparts should require only that the approved source or sources be specified. The procurement drawing should be an SOCD or in conformance with SMD requirements. A periodic sampling procedure must be developed for each system.

5.4.3.4 HCC-1H. Comprised of standard pieceparts which are HCC-2 or HNC based on DM, but are used in hardness dedicated applications. A Hardness Dedicated Item (HDI) is defined as a piecepart or circuit that is nonfunctional during normal operation, but becomes functional as a result of one or more of the nuclear weapon produced environments. Examples include: some radiation detectors; photocurrent compensation devices; bypass capacitors and diodes; and circumvention circuits. The rationale for inclusion of this category is to flag the device or circuit as HC even though a significant DM exists. Piecepart procurement and test requirements are those of the DM determined category, either HCC-2 or HNC.

5.4.3.5 HCC-2. Pieceparts with significant DMs, and though it is

5.4.3.5 HCC-2. Pieceparts with significant DMs, and though it is improbable that they would fail at the specification level, the DM is not great enough to eliminate them completely from further S/V concern. HCC-2 includes pieceparts which are standard and in keeping with the DM intervals presented in 5.5 and 5.6 on DMBP and PCC respectively. HCC-2 pieceparts are procured to MIL-STD or RHA (or possibly 883 compliant) specifications. Periodic testing is called for, but as in the case of HCC-1S pieceparts, the appropriate period and test procedure must be determined for each system.

5.4.3.6 HNC (hardness noncritical). Pieceparts with sufficiently large DMs that anticipated variations in parameter and response present little likelihood of compromising the system. Semiconductor pieceparts in this category must be standard parts, procured to RHA, MIL-STD or SMD (or possibly 883 compliant) specifications. No periodic testing is called for.

5.4.3.7 Passive parts. Passive parts include all nonsemiconductor electronic pieceparts. With one possible exception, passive pieceparts will be categorized in a manner analogous to semiconductors only if warranted by their intrinsic radiation response. Passive parts should not be categorized simply because they are in the control or bias network of an active part. The exception to this applies to any hardness dedicated passive piecepart where by definition the piecepart is activated only in response to the radiation. These pieceparts should be designated HCC-1H.

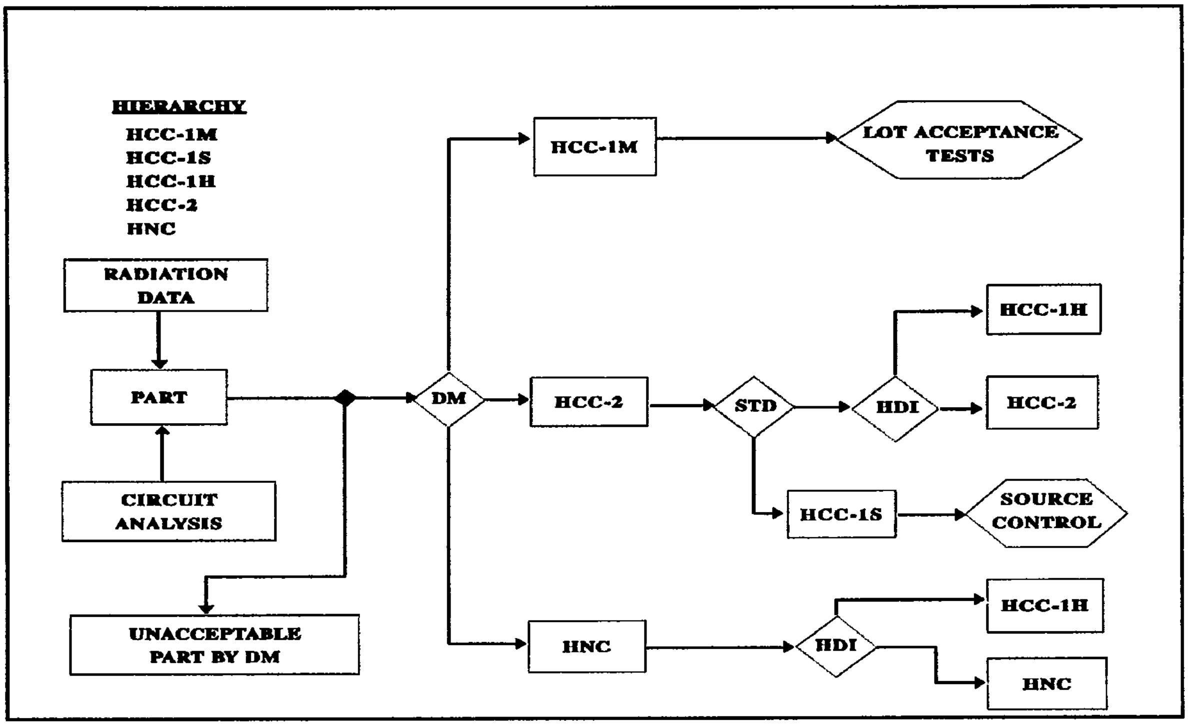


FIGURE 6. HCI categorization flow.

5.4.4 Categorization hierarchy. In view of the HCC definitions, it is possible for a particular piecepart to fall under more than one HCC. In order for the categorization process to have significance, an HCC sensitivity hierarchy is necessary. Figure 6 provides a hierarchy flow diagram based on piecepart controls and the influence these controls have on the system hardness. Figure 7 is a flow chart which shows the relationship between design margins, categorization, lot acceptance, and recategorization. For the decision points shown in the diagram, the logical progression would be as follows:

a. Prior to determining the HCCs, the DMs must be determined for each semiconductor piecepart for the radiation environment of concern. The categorization procedure is then followed for each case.

b. At the first DM decision point, the piecepart is initially placed in HCC-1M, HCC-2 or HNC (or found unacceptable) in accordance with the DM definitions. If the piecepart is determined to be HCC-1M, no further decisions are required, unless subsequent PCC analysis based on additional data indicate the desirability of reclassification and agreement of the acquisition activity is obtained.

c. If the piecepart is initially determined to be either HCC-2 or HNC, the next decision is whether it is standard or nonstandard. If it is found to be nonstandard, it is given a final classification of HCC-1S.

d. An HCC-2 or HNC piecepart that is determined to be standard must then be considered as to whether or not it is an HDI. If found to be an HDI, it will be given a final classification of HCC-1H. If the piecepart is not an HDI, it is classified as HCC-2 or HNC depending on the initial DM classification.

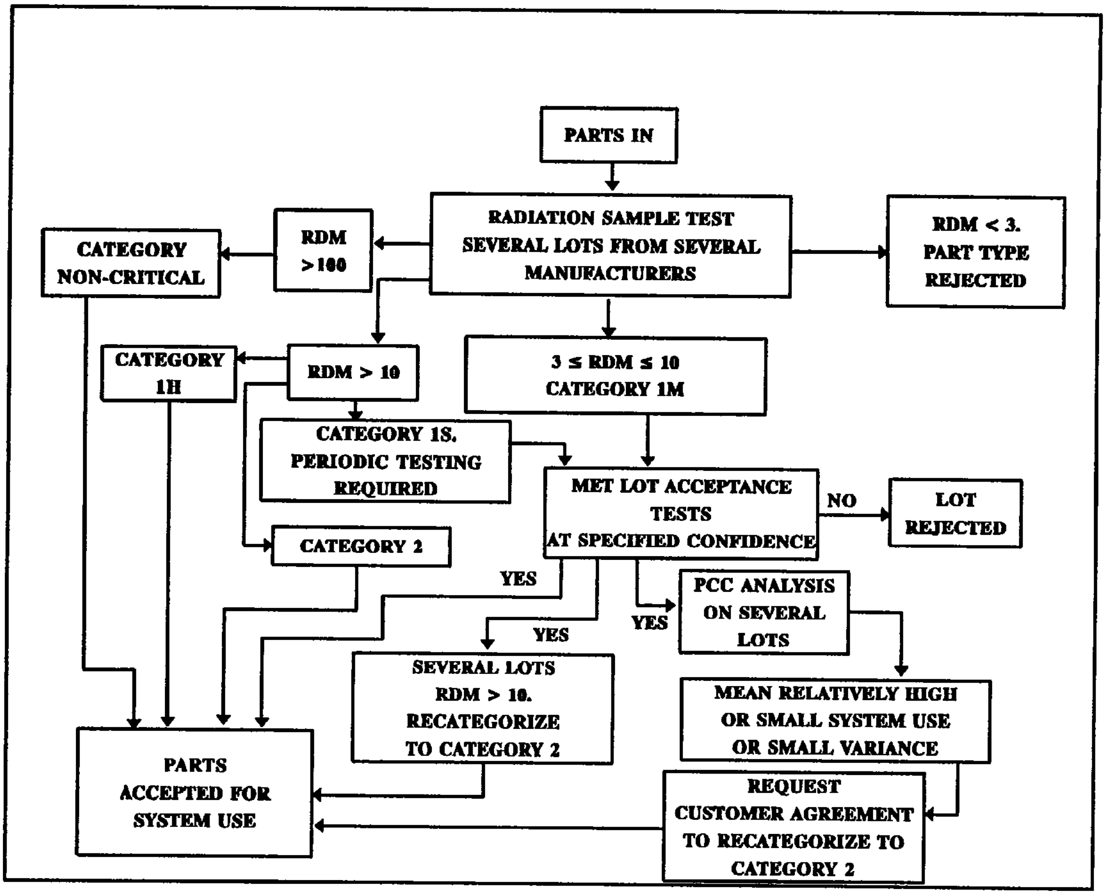


FIGURE 7. Piece part hardness assurancae flow.

5.4.5 Hardness critical processes (HCPs). This classification is most often applied at the circuit board/box, etc., level of construction but is noted here because the HCPs can be directly related to specific pieceparts and the information should be carried in the documentation with reference to the particular circuit or piecepart/socket location.

5.5 DMBP method. The DMBP method described here is an engineering approach and, though related to the lognormal mean, and initially based on statistical considerations, it is not a rigorous statistical approach that will provide numerical solutions to survival requirements. Assumption of the method and breakpoints described below are generally considered conservative with respect to a 99/90 survival requirement at the piecepart level, based on consideration of typically observed within-lot radiation response dispersions and lot-to-lot variations. These P_S and C values do not have a specific statistical basis and must be considered engineering estimates only. A risk is involved, particularly for nonstandard devices, where Government controls are not explicitly required. In this case, both processing and layout may be changed by the manufacturer without notice as long as the device continues to meet the electrical parameter requirements for the part type. Such a change may not affect the electrical performance of a device, but may significantly, adversely affect the device radiation response.

5.5.1 DMBP applicability. The DMBP method is particularly useful for systems having low to moderate S/V requirements. Except in the case of inherently hard device types, it is not as useful for systems with severe S/V requirements. This restriction should be considered as a generalization, and may be tailored to the specific system and technology employed. The rationale for this is that some technologies are typically hard to ionizing dose or neutron fluence levels well above the noted moderate levels, while others may be sensitive below moderate levels. For example, a system may use MOS devices that are intrinsically hard to well above the neutron moderate fluence level, but may be sensitive to ionizing dose at or below the noted moderate level.

5.5.2 HCC-1M reevaluation. It is recommended that pieceparts determined to be HCC-1M by the DMBP method should be reevaluated through application of the PCC method as described in section 5.6. In many cases, pieceparts may qualify to be shifted from HCC-1M to HCC-2 as a result of the reevaluation.

5.5.3 Breakpoints. The breakpoint values provided in table III have been applied to numerous aeronautical and tactical systems in production and in inventory. These values, however, are based on engineering judgement related to typical radiation response data, and should not be considered immutable. Further engineering judgement related to a specific system under consideration may call for modification of the recommended breakpoints. S/V engineering personnel may shift the breakpoints if they feel it is necessary or desirable in order to tailor the DMBP method to the particular system. It should be kept in mind that the DMBP is based on the logarithmic mean of the test sample distribution and lowering of the minimum acceptable DM value of 3 can produce an unacceptable situation.

TABLE III. Relationship between HCCs and RDMs.

	HCC-1M	HCC-2	HNC
RDM Neutron or ionizing dose	2-3 < RDM ≤ 10	10 < RDM ≤ 100	RDM > 100

5.5.4 DMBP procedure. The steps in the application of the DMBP method are as follows:

a. Determine through circuit analysis the maximum or minimum value of the parameter that will cause circuit failure, PAR_{FAIL}.

b. Determine the logarithmic mean radiation failure level of the test sample distribution (see the caution note given in section 5.3.3 on lognormal computations), $\overline{\ln(R_{FAIL})}$

c. Take the antilog of the results of step b. to find the mean failure level

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

d. Determine the RDM by taking the ratio of the results of step c. to the specification radiation level, R_{SPEC}.

$$RDM = \frac{R_{MF}}{R_{SPEC}} = \frac{e^{\overline{\ln(R_{FAIL})}}}{R_{SPEC}}$$

e. Compare the obtained RDM to the breakpoints shown in table III to determine the RDM related category of the device. The established breakpoints occur at RDMs equal to 3, 10 and 100. Pieceparts with an RDM equal to or less than 3 are unacceptable; greater than 3 and equal to or less than 10 are HCC-1M; greater than 10 but equal to or less than 100 are HCC-2; greater than 100 are HNC.

f. The determined category information is then used in conjunction with the control and test requirements discussed in sections 5.2.1.2 and 5.8.

5.5.5 DMBP example. As an example of the DMBP method, consider the following experiment for the ionizing radiation change in input bias current, delta I_B, for a sample of five LM108 amplifiers.* The system in this example has an ionizing dose specification level of 150 krads(Si) which is applicable to the pieceparts. The steps in the DMBP procedure are as follows:

* For simplicity, the data for each of these examples are drawn from a single lot. In fact, categorization should be based on multi-lot data. See section 5.8 for a full discussion of testing and data analysis.

Step 1 - Through circuit analysis, determine the maximum allowable change in bias current for proper circuit operation, in this case, 10 nA. Then

$$PAR_{FAIL} = 10 \text{ nA}.$$

Step 2 - Irradiate the test samples in accordance with section 5.8.4 at increasing dose levels until all of the parts have reached or exceeded the PAR_{FAIL} value of a change of 10 nA. (Note that delta I_B increases with increasing dose.)

Step 3 - Plot delta I_B versus ionizing dose as shown on figure 8 and determine the failure dose, R_{FAIL}, for each part. Radiation response data were taken at four dose levels and the failure dose was determined for each device as shown in table IV.

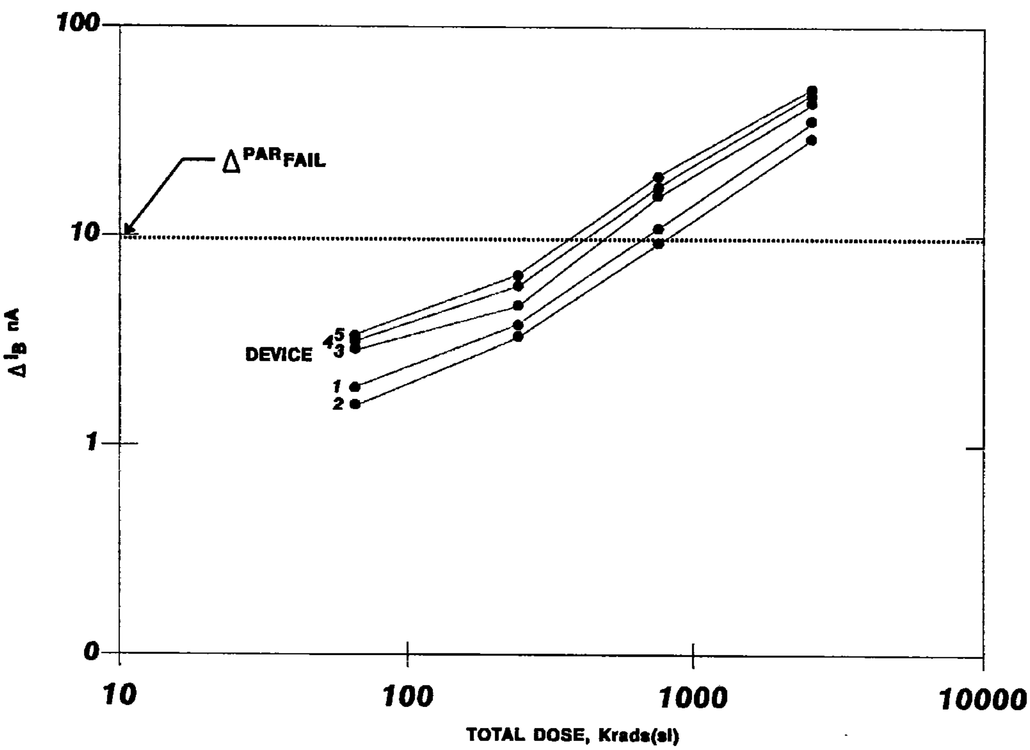


FIGURE 8. Bias circuit as a function of dose (for LM108 amplifiers).

TABLE IV. LM108 OP AMP failure levels.

Test part	R_{FAIL} krads(Si)
1	650
2	800
3	500
4	420
5	350

Step 4 - Determine the mean failure dose using log normal statistics as shown in section 5.3.3.

$$R_{MF} = e^{\overline{\ln(R_{FAIL})}} = 521\ krads(Si)$$

Step 5 - Calculate the RDM

$$RDM = \frac{R_{MF}}{R_{SPEC}} = \frac{521}{150} = 3.5$$

Step 6 - Compare the determined RDM with the breakpoints given in table III to find the HCC of the device. The RDM of 3.5 lies between the minimum value of 3 and the HCC-1M/HCC-2 breakpoint of 10, so the piecepart type is acceptable and is category HCC-1M.

Step 7 - Apply the guidelines in sections 5.2.1.2 and 5.8 for applicable control and test requirements.

5.6 PCC method. The PCC method (used in industrial quality control - see 6.42) is a fully statistical approach that makes use of the variability of the radiation characterization failure values obtained from the test data, the required Pprobability of Ssurvival (P_S) and Cconfidence (C) values and the test sample size to determine a PCC value that is used to categorize each device type. The PCC method is applicable to any hardened system, but is generally most useful for application to systems with relatively stringent survivability requirements or when sample sizes are small. For this method, a PCC (equivalent breakpoint) value is derived for each piecepart type with the aid of one sided tolerance limit factors and characterization data for that piecepart. The PCC method may also be used in conjunction with the DMBP method as described in section 5.7 for application to moderate and lower level requirements systems (see 6.43 through 6.46).

5.6.1 PCC method benefit. The PCC method may be used as a guide in placing or reclassifying parts into HCC-2 when the design margin is less than ten and an adequate statistical data base consisting of several lots is available. Since lot acceptance testing is required for HCC-1M pieceparts and is not required for HCC-2, it is important from a cost and control complexity standpoint to have as few HCC-1M pieceparts as possible. The PCC approach provides a method more rigorous than the DMBP method for determining this critical division point. PCC procedures are similar to those of the DMBP method in that a part's DM is related to a calculated PCC value to determine if the device is HCC-1M or HCC-2. Derivation of the DM from the lognormal mean of the characterization data is identical to the procedure used for the DMBP method.

5.6.2 PCC value. The method provides a separate PCC value for each piecepart type for a given P_s, C and sample size. This value is developed in consideration of the typically used moderate pieceparts survivable requirements of 99/90 related to the HCC-1M/HCC-2 division point. The recommended small DM "unacceptable" bound and the division between HCC-2 and HNC are based on engineering considerations. These could also be treated statistically if so desired, provided that P_s and C values for these points for a particular system are agreed upon.

5.6.3 Small DMs. For devices having a small DM, the recommended minimum DM value of 2 to 3 is applied here as in the DMBP method. That is, if the DM is equal to or less than the selected minimum, the piecepart is unacceptable. This is determined from the DM calculation prior to developing the PCC value. (As noted earlier, applying this minimum DM value may not be practical for devices exposed to very high dose or fluence levels, and engineering judgement is called for.) When the PCC method results in a design margin less than ten, specific agreement should be obtained from the acquisition activity before the part is placed in category HCC-2.

5.6.4 HCC-2/HNC breakpoint. The recommended approach to specifying the division point between HCC-2 and HNC is to apply the appropriate breakpoint value derived by the DMBP method. The rationale for this is that the DMBP method provides a conservative approach that should be adequate for most systems. That is, if the device is HNC by the DMBP method then it would undoubtedly also be HNC for the more exacting PCC method. In addition, the significance in terms of cost and complexity is small between HCC-2 and HNC (in contrast to the difference between HCC-1M and HCC-2, where it is substantial).

5.6.5 PCC factors. Before the method used for determining the PCC value is presented, a discussion of the factors used is in order (see the caution note given in section 5.3.3 on lognormal computations). The data variability is represented by the standard deviation, s, and is calculated using the R_{FAIL} values taken from the test data. Because we are dealing with the lognormal case, this factor is represented as the lognormal standard deviation, $s_{ln(RFAIL)}$ which is the standard deviation of the logarithms of the R_{FAIL} radiation values and is calculated using equation 5.3.3-2.

$$s_{\ln(R_{FAIL})} = \left(\frac{1}{n-1}\sum_{i=1}^{n}[\ln(R_{FAIL_i}) = \overline{\ln(R_{FAIL}]^2}\right)^{1/2} \qquad \text{Eq. 5.6-1}$$

where: $R_{FAIL(i)}$ is the radiation failure level for the i^{th} device, n is the sample size and the remaining term, the logarithmic (geometric) mean, is

$$\overline{\ln(R_{FAIL})} = \frac{1}{n}\sum_{i=1}^{n}\ln(R_{FAIL_i}) \qquad \text{Eq. 5.6-2}$$

5.6.6 Calculating the PCC value. The survival probability and confidence level are introduced into the calculations by multiplying $s_{\ln(RFAIL)}$ by the factor K_{TL}. K_{TL} is called the one sided tolerance limit factor and is selected from a table of tolerance limits (appendix, table IX - also see 6.47. K_{TL} is a function of the sample size, n, the cumulative proportion of the distribution, P_{DIST}, and the confidence level, C (i.e., $K_{TL}(n, P_{DIST}, C)$). For example, for a sample size n, a P_s = 99 percent and a C = 90 percent, if the characterization test were repeated many times, 90 percent of the time (90 percent confidence), 99 percent of the $\ln(R_{FAIL})$ values would fall in a range equal to or greater than the mean minus K_{TL} times the lognormal standard deviation. That is, for the lognormal distribution, 90 percent of

$$\ln(R_{FAIL}) \geq \overline{\ln(R_{FAIL})} - K_{TL}s_{\ln(R_{FAIL})}$$

The PCC value against which the RDM is compared is

$$PCC = e^{[K_{TL}s_{\ln(R_{FAIL})}]} \qquad \text{Eq. 5.6-3}$$

Note that requiring RDM > PCC to categorize a part as HCC-2 is equivalent to requiring that

$$\overline{\ln(R_{FAIL})} \geq \ln(R_{SPEC}) + K_{TL}s_{\ln(R_{FAIL})}$$

5.6.6.1 Adjusting PCC. Increasing P_{DIST} or C, or decreasing the sample size increases K_{TL} and consequently increases the PCC value. A larger PCC value (i.e., raising the acceptance criterion for an HCC-2 piecepart) will likely increase the number of piecepart applications categorized as HCC-1M, which will in turn increase the parts procurement complexity and HA program costs. Increasing the sample size, n, generally will increase the cost of the radiation characterization tests applied to parts qualification. However, this added cost may be more than offset during production parts procurement since increasing the sample size provides a lower value of K_{TL} which in turn may reduce the number of part types falling into HC-1M. The values of P_{DIST}, C and n may be varied as trade-offs between the level of HA desired and the amount of funding available. Values of P_S = 0.99 and C = 0.90 at the piecepart level are often applied as achievable, generally affordable goals if the system does not have other specified values.

5.6.7 PCC radiation environment based procedure. The steps in the application of the PCC method are as follows:

a. For a particular piecepart type, determine through circuit analysis the maximum or minimum value of the radiation affected parameter(s) that will cause circuit failure, PAR_{FAIL}.

b. Determine the lognormal mean radiation failure level of the parts test distribution as given by equation 5.6-2.

$$\overline{\ln(R_{FAIL})}$$

c. Take the antilog of the results of step b. to find the normal space mean failure level,

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

d. Determine the RDM by taking the ratio of the results of step c. to the specification level, R_{SPEC},

$$RDM = \frac{R_{MF}}{R_{SPEC}}$$

e. If the RDM = 3 or less, the part should be considered unacceptable for use in the system; a substitute piecepart or other hardening approach should be implemented.

f. If the RDM > 100, the piecepart should be accepted as an HNC category device.

g. Determine the PCC value for the device type by using equations 5.6-1, 5.6-2 and 5.6-3,

$$PCC = e^{[K_{TL}(n, P_{DIST}, C)\, s_{\ln R_{FAIL}}]}$$

h. For devices falling within the interval determined by steps e. and f. (i.e., 3 < RDM < 100) the category will be either HCC-1M or HCC-2. The category is determined by comparing the RDM value to the PCC value for the device. If the RDM found in step d. is greater than the PCC value, the piecepart is HCC-2, and if it is less than, or equal to the PCC value, it is HCC-1M.

5.6.7.1 PCC method, radiation based, example 1. Consider the ionizing radiation induced change in op-amp input bias current, delta IB, for LM108 amplifiers. (This is the same data set used in the DMBP method example presented in table IV and figure 8.) The ionizing dose specification for this sample of five pieceparts is 150 krads(Si). All five pieceparts were tested to and above the analytically determined PAR_{FAIL} value. the steps in the procedure are as follows:

Steps 1 through 5 - These steps for the PCC method are identical to the same steps described for the DMBP method in section 5.5.5 based on the response data of table IV and the plot on figure 8. These steps produce an RDM value of 3.5 for this piecepart type.

Step 6 - Calculate the logarithmic standard deviation, $s_{ln(RFAIL)}$, in accordance with equation 5.6-1. This value will be used in determining the PCC value with which the RDM from step 5 will be compared. Calculated values for this example are given in table V for application to equation 5.6-1 for determination of $s_{ln(RFAIL)}$.

TABLE V. PCC example values.

Test part	R_{FAIL} (krads	$\ln(R_{FAIL})$	$[\ln(R_{FAIL})-\overline{\ln(R_{FAIL})}]$	$[\ln(R_{FAIL})-R_{MF}]^2$
1	650	13.385	0.222	0.0493
2	800	13.592	0.429	0.184
3	500	13.122	0.041	0.00168
4	420	12.948	-0.215	0.0462
5	350	12.766	-0.397	0.1576

Find the geometric mean to be used in the standard deviation equation by summing the natural logarithms of the failure dose for each device and dividing by the sample size (equation 5.6-2).

$$\overline{\ln(R_{FAIL})} = \frac{65.813}{5} = 13.163$$

Find the standard deviation, (equation 5.6-1),

$$s_{\ln(R_{FAIL})} = \left(\frac{1}{n-1}\sum_{i=1}^{n} [\ln(R_{FAIL_i}) - 13.136]^2\right)^{1/2} =$$

Step 7 - Determine the appropriate one sided tolerance factor, K_{TL}, from table

$$\left(\frac{0.4388}{4}\right)^{1/2} = 0.331$$

IX in the appendix. For this example, the parameter values for entry into the tables are: $P_s = 0.99$, $C = 0.90$ and $n = 5$. The corresponding K_{TL} value (table IXb) is 4.666.

Step 8 - Determine the PCC value (equation 5.6-3) by taking the antilog of the product of K_{TL} and $s_{\ln(RFAIL)}$

$$PCC = e^{(4.666)(0.331)} = 4.69$$

Step 9 - Categorize the part type as follows:

RDM = 3.5 from step 5

PCC = 4.69 from step 8

The DM is less than the PCC value. Consequently this part type is categorized HCC-1M, and the appropriate procurement controls and lot acceptance tests are required.

5.6.7.2 PCC method, radiation based, example 2. This is an example of measured neutron fluence to failure testing of a sample of 2N2222 transistors. The data used is given in table VI for twenty transistors composed of two lots. (A probability plot of this data is shown on figure 3.) The specification fluence is 1E13 n/cm^2 (1 MeV SDE), and the required survival probability and confidence levels are 0.99 and 0.90 respectively.

Step 1 - First find the geometric mean (equation 5.6-2) of the sample by taking the logs of the individual failure fluence values, sum the log values and divide by the sample size. This produces a value of 31.92.

Step 2 - The antilog of this value is the mean fluence to failure:

$$RMF = e^{31.92} = 7.3 \times 10^{13}.$$

Step 3 - Determine the DM by taking the ratio of R_{MF} to the specification level R_{SPEC}:

$$RDM = R_{MF}/R_{SPEC} = 7.3 \times 10^{13}/1 \times 10^{13} = 7.3$$

Step 4 - The first step in determining the PCC value is to find the lognormal standard deviation in accordance with equation 5.6-1. In this case (table VI),

$$s_{\ln(R_{FAIL})} = 0.40$$

Step 6 - Determine the PCC from equation 5.6-3:

$$PCC = e^{(3.052 \times 0.40)} = 3.39$$

Step 7 - Compare the RDM and PCC values to determine the HCC:

$$RDM = 7.3 > PCC = 3.39.$$

Thus, consideration could be given to reclassifying the part HCC-2.

5.6.8 PCC parameter based procedure. The parameter based procedure is similar to that applied to the radiation based procedure discussed earlier. In this case, parameter values for all pieceparts in the sample irradiated to a particular level are used for the sample distribution. This mean of the sample parameter response distribution is related to the analytically determined PAR_{FAIL} value to determine the PDM. Consideration must be given to the direction of parameter change with increasing radiation. That is, whether the parameter value increases or decreases with radiation. The PDM (equation 5.4.1-4) is related directly to the PCC value (equation 5.6-3) for the sample to determine if the piecepart is HCC-1M or HCC-2. In order to be HCC-2, the following criteria must be met:

for increasing PAR values,

$$PDM = \frac{PAR_{FAIL}}{e^{[\overline{\ln(PAR_{RAD})}]}} \geq PCC = e^{[K_{TL} s_{\ln(PAR_{RAD})}]}$$

which is equivalent to requiring that

$$\overline{\ln(PAR_{RAD})} < \ln(PAR_{FAIL}) - K_{TL} s_{\ln(PAR_{RAD})}$$

For decreasing PAR values,

$$PDM = e^{\frac{[\overline{\ln(PAR_{RAD})}]}{PAR_{FAIL}}} \geq PCC = e^{[K_{TL} s_{\ln(PAR_{RAD})}]}$$

which is equivalent to requiring that

$$\overline{\ln(PAR_{RAD})} > \ln(PAR_{FAIL}) - K_{TL} s_{\ln(PAR_{RAD})}$$

TABLE VI. Fluence-to-failure for twenty 2N2222 transistors (sampled from two different lots).

Failure criterion $h_{FE}(FAIL) = 40$

Lot 1		Lot 2	
ϕ_{FAIL} (10^{13} n/cm²)	ln ϕ_{FAIL}	ϕ_{FAIL} (10^{13} n/cm²)	ln ϕ_{FAIL}
7.77	31.98	7.86	32.00
6.12	31.75	8.92	32.12
6.38	31.78	8.71	32.15
6.15	31.75	11.23	32.10
5.04	31.55	8.25	32.04
5.00	31.54	11.08	32.34
5.02	31.55	10.53	32.29
4.25	31.38	10.00	32.24
4.33	31.41	11.43	32.37
3.60	31.21	15.56	32.68
mean: ln ϕ_{FAIL}	31.59		32.25
Standard dev: $S_{ln\phi}$	0.23		0.20
	Both lots	combined	
mean: ln ϕ_{FAIL}	31.92		
Standard dev: $S_{ln\phi}$	0.40		

5.6.8.1 PCC method, parameter based example. In this example, categorization to ionizing dose of a sample of 2N3637 transistors is made on the basis of collector leakage current, ICBO (table VII).

5.6.8.1.1 Example requirements. The system in this example has the following requirements: R_{SPEC} = 30 krads(Si); P_s = 0.999 and C = 0.95. The worst case circuit failure value, PAR_{FAIL}, for this device is 30 nA. The test sample size used here is n = 5.

Step 1 - The test plan was to irradiate the test samples at incremental, increasing dose levels until all of the parts reached the PAR_{FAIL} value of 30 nA. However, in the course of testing, none of the ICBO values had reached PAR_{FAIL} at 600 krads(Si), which is 20 times the R_{SPEC} value of 30 krads. A plot of this data is shown on figure 9.

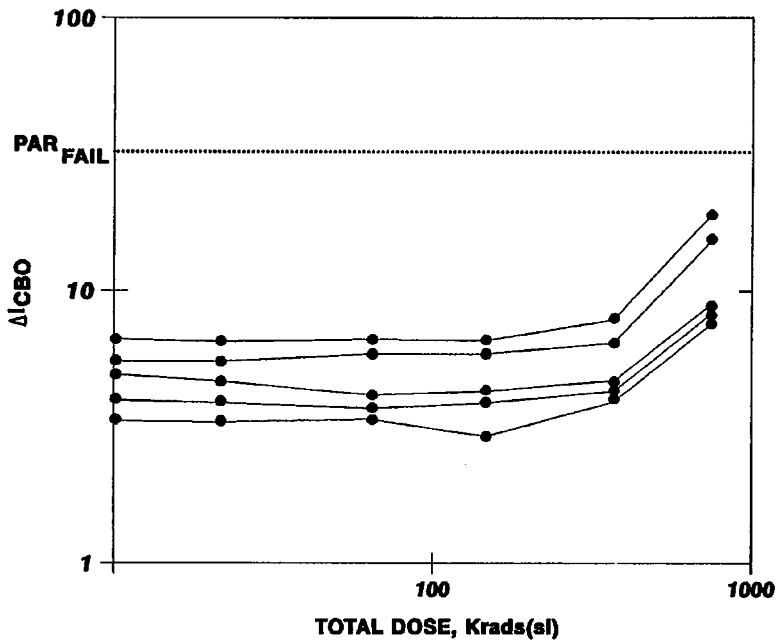


FIGURE 9. I_{CBO} vs Total dose for 2N3637 transistors.

5.6.8.1.2 Categorization calculation. Since the R_{FAIL} values cannot be obtained from the graph, the piecepart application cannot be categorized by the method described in section 5.6.7. In this case, the PAR_{RAD} values taken at the R_{SPEC} level will be used to calculate the parameter response distribution, the parameter based DM and a corresponding PCC value from which the piecepart type can be categorized. The categorization rules are as described for the radiation based method. That is, if the DM is equal to or less than the PCC value, the piecepart is HCC-1M. If the DM is greater than the PCC value, it is HCC-2.

Step 2 - Using the data from table VII of PAR_{RAD} values measured at R_{SPEC}, determine PDM for parameter values that increase with cumulative radiation, (equation 5.4-3),

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

where

$$e^{\overline{[\ln(PAR_{RAD})]}} = e^{1.28} = 3.6nA$$

Therefore,

$$PDM = \frac{30nA}{3.6nA} = 8.33$$

TABLE VII. 2N3637 transistor parameter values.

2N3637 test part	PAR_{RAD} I_{CBO} (nA)	ln (PAR_{RAD})
1	4.1	1.41
2	4.6	1.53
3	3.2	1.16
4	3.5	1.25
5	2.9	1.06

Step 3 - Using the PAR_{RAD} values rather than the R_{FAIL} values in equation 5.6-1, determine

$$s_{\ln(PAR_{RAD})} = 0.189$$

Step 4 - Determine the PCC value using $s_{\ln(PARRAD)} = 0.189$ from Step 3 and $K_{TL} = 7.502$ from appendix table IX for n = 5, $P_s = 0.999$ and C = 0.95. Applying equation 5.6-3 to PAR_{RAD} values,

$$PCC = e^{[(7.502)(0.189)]} = 4.13$$

Step 5 - Categorize the part application as follows:

PDM = 8.33 from step 2
PCC = 4.13 from step 4

Since the PDM is greater than the PCC value, this piecepart can be considered for recategorization to HCC-2. Although the data plots of figure 9 are not linear above 150 krads(Si), they are linear well above the critical value of R_{SPEC} = 30 krads(Si).

5.7 Combined DMBP/PCC methods. Figure 7 shows how the DMBP method described in section 5.5 may be used in combination with the PCC method presented in section 5.6. In both moderate and severe requirements cases, the DMBP method is often used as a first screen to categorize all potentially susceptible pieceparts. As additional data is accumulated on HCC-1 parts through more characterization or lot acceptance testing, recategorization may be possible. PCC analysis should be done on that additional data, and if it reveals that the mean is consistently high or there is a very small variance, the contractor should seek SPO/PMO agreement to recategorize the part as HCC-2. Similarly, if the data reveal a consistent RDM > 10, then recategorization should be sought. Very limited system use of a part could be another reason to request recategorization.

NOTE: Recatigorization is done with customer concurrence after trda-offs between the cost of testing, the cost of device failure, and the increased risk of device failures due to reduced testing. Estimating this increased risks is a major problem involving a determination of how well the tested parts represent future procurements. For example, if future procurements will come from the same parent populations the tested devices, recatigorization can be done for RDM>PCC. However, the problem is rarely that simple and most often it is necessary to consider how many lots and device manufacturers were involved in the characterization data and what variations over time must be considered for each device manufacturer.

5.8 Hardness assurance testing. Two major forms of testing are applicable to HA, though the nomenclature may differ between systems. These are:

Qualification testing, and
Lot acceptance testing.

5.8.1 Qualification. Qualification testing requires that sufficient parts data are derived or developed to establish an acceptable baseline indicating that the piecepart type meets acceptance criteria for both the radiation specification and the HA program requirements. Piecepart qualification is accomplished through characterization testing based on variables data (see 5.3.2.3 herein). This provides an understanding of the device parametric changes as a function of the applied radiation stress. All radiation sensitive devices must be qualified prior to the end of the Full Scale Engineering Development (FSED) phase. (This marks the end of the design and development phase, prior to production initiation.)

5.8.2 Lot acceptance. LAT is performed by the contractor, and is required for production equipment pieceparts determined in the qualification testing program to be especially sensitive (i.e., HCC-1M). Lot Acceptance Criteria (LAC) are developed from qualification program data and may take the form of either variables or attributes data depending primarily on the design margin for the most critical application, piecepart cost, testing costs, etc. (LAT should not be confused with Quality Conformance Inspection (QCI).) QCI is the terminology applied to inspection and testing carried out by the manufacturer during piecepart production (see MIL-I-38535, appendix A).

5.8.3 <u>Standardization and procurement</u>. All qualification and lot acceptance testing should be carried out in accordance with MIL-STD-883 or MIL-STD-750, method 1019 for ionizing dose or method 1017 for neutron testing. (Exceptions to these standard methods may be made where it can be shown that the method requirements conflict with a logical approach to meeting a specific system's requirements.) The test agency that carries out the testing is an important consideration, and it may be best from the bookkeeping, control, timing, and failed lot recovery aspects if the vendor performs the radiation tests. However, many vendors do not have a radiation testing capability and testing must be performed by the contractor or a third party that does have the testing capability. Procurement of the test pieceparts and timing of the radiation testing are important considerations and must be related to the particular system design, qualification and production periods. Adequate lead time must be allowed for parts procurement to allow for normal lead time plus any additional time related to radiation testing. This is especially important for pieceparts requiring lot acceptance testing where the lack of a timely acquisition can delay production.

5.8.4. <u>Test considerations</u>. In addition, the testing sequence of radiation environments and test samples must be carefully considered in advance. Often, the test sample used in the transient gamma tests is also used for neutron or ionizing dose testing, or both. This is an acceptable approach since, under appropriate test conditions (i.e., no induced gamma or latchup burnout and insignificant accrued dose), the devices are typically not degraded. A consideration of importance to test and data acquisition timing is neutron activation of the devices in the test sample. High fluence irradiation will generally result in activation, and even moderate fluences will activate the materials found in some devices. This often requires that the test parts be held in a controlled area at the test facility for possibly several months. Fast-burst reactors cause less activation than other types of reactors. If in-situ or in-flux radiation data are not taken, the delay encountered for remote testing could seriously affect timely qualification or lot acceptance.

5.8.5 <u>Radiation test plan</u>. Radiation test plans are required to cover all piecepart radiation environmental testing. It includes both general and specific test issues. The general issues include: (1) test objective, (2) responsible organization and personnel, (3) types of facilities to be used, (4) equipment required for measurement and calibration procedures, (5) a general description of the test procedures to be followed, (6) method of test sample selection, for both qualification and LAT, (7) dosimeter types, application and read-out information, (8) a description of record keeping and documentation, including sign-off forms, data format and identification of the test conditions with the test data, and (9) final data processing and analysis, including LAC application. The specific issues include: (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 wafer lot numbers; (2) reference to applicable MIL-STD or other employed methods; (3) device bias and operating conditions during the radiation exposure; (4) specific radiation facility and radiation flux, fluence levels, and incident radiation spectra for each exposure; (5) piecepart placement with respect to the radiation source; (6) test temperature; (7) electrical parameter pre-irradiation values and test conditions; (8) test circuit diagrams showing test device interconnection during each measurement; (9) whether electrical measurements are to be made in-flux (i.e., while being irradiated), in-situ (i.e., in the radiation test position but not while being irradiated), or remote (i.e., not in the radiation test position); (10) electrical parameter measurements required and device operating conditions during the measurements; (11) a prediction of the expected range of response including signal magnitudes, timing and annealing considerations for each test point to be monitored; (12) a list of all test fixtures and test equipment; and (13) the format in which the data are recorded. The test plan must be reviewed by all principals to ensure that it adequately reflects the system requirements. In general, Government approval of the test plans and procedures is required prior to implementation.

5.8.6 Radiation test facilities. An important aspect of the hardening and HA programs is the selection of the proper radiation facility, or source. Factors to consider include the type of radiation, magnitude, deposition rate, spectra pulse duration and the radiation facility's abilities to simulate the desired environments and the dosimetry and radiation environment quality assurance program. Limitations are often encountered in attempts to closely simulate the specification environments, and work-around solutions must be employed.

5.8.6.1 Ionizing dose test facilities. The recommended facilities for ionizing dose testing are cobalt-60 (Co-60) sources since they are relatively inexpensive to operate and provide an easy means of testing. Rates of delivery can be controlled by using stronger or weaker sources as well as by sample placement with respect to the source and the use of shielding. Higher delivery rates can be obtained with use of a Linear Electron Accelerator (LINAC) operating in a repetitive pulse mode. However, LINAC testing costs are much higher, test volumes are limited and the test procedures tend to be more difficult. Most ionizing radiation "permanent" damage is related to bulk and interface trapped charge. However, some permanent damage due to displacement effects is associated with high energy electron beam irradiations and can become significant at high dose levels (e.g., megarad region). In addition, test equipment manufactured by ARACOR is available for ionizing dose testing of devices at the wafer level (see 6.48). This facility provides relatively low energy x-rays to individual, selected die on the wafer, and is used in conjunction with a production line probe station. Since this involves wafer level testing, it usually falls to the semiconductor manufacturer to perform the tests. Radiation procurement specifications may be provided to the manufacturer by the contractor for lot acceptance criteria based on the wafer level sample test data. A listing of many available radiation facilities and their capabilities is provided in 6.49 herein.

5.8.6.1.1 Simulation fidelity. Ionizing dose testing is complicated by the differing deposition rates and types of radiation that may be specified for a given system. Ionizing dose may be delivered as contributions from the prompt gamma and x-ray pulses (nanoseconds), the delayed gamma pulse (microseconds), neutron induced secondary gammas (milliseconds to seconds), debris and fallout (days to months or greater), and from natural space radiation (photons, electrons and charged particles) for satellite applications (years). Thus, the obvious difficulty is that of adequately matching the test environment to the specification environment. Each system must be reviewed by knowledgeable S/V personnel to determine the most appropriate source to provide an acceptable test damage equivalence to the imposed specification.

5.8.6.1.2 Dosimetry. Test data may not be valid without considerable attention to obtaining correct radiation dosimetry. While there are a number of valid techniques, the most commonly used system is Thermoluminescent Dosimetry (TLD). The ASTM and DoD have approved a standard for use of TLD dosimetry in radiation testing, ASTM E668, "Standard Practice for the Application of Thermoluminescent Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation Hardness Testing of Electronic Devices." This standard gives considerable detail on correction procedures (also see references 6.50 and 6.51). Calibration of the TLD system must be traceable to the National Institute for Standards and Technology to insure accuracy.

5.8.6.2 Neutron test facilities. The most widely used sources of neutrons for HA testing of electronics are nuclear reactors of either the TRIGA or Fast Burst Reactor (FBR) type. Water moderated reactors (e.g., TRIGA type) might also be used, although test and dosimetry problems tend to be greater than in an FBR. The DNA TREE Simulation Facilities Handbook (reference 6.49) provides information on 18 pulse reactor facilities. Under free-field conditions, FBRs provide the larger ratio of neutron-to-gamma radiation dose and provide a higher average neutron energy which in turn will produce less residual radioactivity in the samples. Properly used, with proper facility attention to dosimetry, either type of facility can provide satisfactory HA testing, though the FBR is recommended because there are fewer potential problems involved.

5.8.6.2.1 Other sources. Isotopic radioactive sources and accelerators can also be used as neutron sources, but their utility is generally limited because of their low output. The essentially 14 MeV neutron energy from the D,T reaction must be normalized to the commonly used 1 MeV SDE for data application and comparison.

5.8.6.2.2 Reactor issues. Along with neutrons, nuclear reactors emit gamma photons that can also cause degradation of electronic pieceparts. The neutron to gamma ratio can often be adjusted through test device placement with respect to the reactor and selective shielding to simultaneously meet the system specified neutron and ionizing dose requirements. This is often a preferred procedure when the combined damage is not expected to be large. However, it is usually desirable to obtain a high neutron-to-gamma ratio when performing neutron damage studies. It should be emphasized that whenever shielding is used in a reactor to change the neutron/gamma ratio, the neutron spectrum of the exposure is also changed. This requires that the 1 MeV SDE fluence be recalculated for the new spectrum for dosimetry accuracy. The highest neutron-to-gamma ratios can be obtained at FBRs with high atomic number shields, such as lead (table VIII). Approximate ("rule-of-thumb") neutron to gamma ratios are given in table VIII: values may vary between reactors and test point with respect to the reactor core. The lowest neutron-to-gamma ratios are obtained at water moderated or TRIGA reactors with cadmium or CdO loaded polyethylene shielding.

5.8.6.2.3 Dosimetry. Neutron dosimetry must be performed, usually with sulfur pellets or other monitors and previously determined spectrum correlation factors, to provide a fluence measurement in terms of 1 MeV (SDE). (See ASTM Standard E 722 for a description of the SDE normalization procedure.) The gamma dose measurements are usually made with TLDs. (See ASTM Standard E688 for TLD procedures.) The reactor facility must have intensity maps and spectrum correlation factors. The experimenter is advised to thoroughly review the test requirements with the facility's personnel in advance of the test.

TABLE VIII. Approximate neutron to gamma ratios.

n/cm^2 (1 MeV SDE)/rad(Si)

	TRIGA or water moderated	FBR
Free-field	3 to 9 x 10^8	4 x 10^9
Attenuated (2" lead)	7 x 10^9	1.4 x 10^{10}

5.8.7 Qualification testing. Piecepart qualification is carried out during FSED and is the procedure by which each piecepart type is determined to be acceptable for use in the system. Qualification testing should be accomplished as early as practicable in the design phase commensurate with the firmness of the design and parts selection. An initial phase of the parts qualification program should be the evaluation of the FSED applied design data. It may be possible, particularly where there are large DMs, to base the qualification acceptance on the existing data. Engineering judgement is called for in interpreting the acceptability of both older and newly developed data.

5.8.7.1 Test levels. Radiation levels for piecepart qualification testing should be based on both the specification levels and the anticipated piecepart response. Typically, a full spectrum of test levels would cover more than two orders of magnitude. Radiation levels would range from the specification level (or possibly somewhat below) to two orders of magnitude above the specification level where it can be established that the piecepart is HNC. However, engineering judgement, based on historical data and predictions, may be applied in many cases to reduce this broad range of testing levels. Typically, one would like to have data points in the vicinity of the specification level for application to the system's survivability verification requirements. However, if a piecepart shows no significant response at a higher radiation stress level, it will generally be acceptable at a lower level. (This does not always hold true, particularly in the case of ionizing dose where competing damage mechanisms may result in greater parametric changes at some lower level than they do at a higher level.) As a result, lower stress level tests may not be necessary where predictions indicate the response will be negligible.

5.8.7.1.1 Highest level. An effort should be made to run the tests up to a radiation level which is sufficiently large so that all pieceparts in the sample reach the device failure level, PAR_{FAIL}. There may be cases where this is not possible and where only a portion, or none of the parts has failed. If a sufficient portion of the test parts has failed, the failed portion may constitute an acceptable assessment sample and may be used to establish the statistical failure data. If an insufficient portion of the sample has reached failure, then the characterization should be done in terms of the parameter based procedure described in section 5.6.

5.8.7.1.2 Suggested levels. For typical qualification data, a minimum of three data sets must be taken to provide some knowledge of the parts' response with increasing radiation stress. That is, electrical parametric data on all parts in the sample must be taken for three radiation dose or fluence levels. In addition, a data set should be taken at one order of magnitude or more above the specification level to assure that the piecepart meets HCC-2 requirements. A suggested set of radiation test levels are: the specification level; 3X, 10X, and 50X or 100X above the specification level. For very high gamma or neutron specification levels, the recommended test levels above the specification level may not be practical. However, several data sets should be taken at least up to the specification level, and based on engineering judgement, above the specification level as far as is practicable.

5.8.8 Multi-lot testing. Within-lot variability is usually statistically handled by use of the PCC method described in section 5.6. However, most systems procure more than one lot of parts for qualification and production purposes. Furthermore, even a single inspection lot may consist of several sub-lots so the lot-to-lot variations may still be of interest even when a single inspection lot is provided. This leads to the question of multi-lot variability, which is typically larger than within-lot variability, particularly when more than one vendor provides lots and the lots are procured over a period of time. The multi-lot assessment procedure described here makes use of the variables data developed for parts qualification, supplemented by additional similar data if required. (The reader is referred to sections 6.52 and 6.53 for a more detailed presentation of this approach.) This method provides the procedures for determining the electrical parameter end-point limits appropriate to the multi-lot population distribution. Parameter end-point limits are the minimum or maximum parameter values that are estimated to be within the acceptable range for a given survival and confidence requirement. End-point limits may be used as estimated design parameter limits or as the basis for LAC for lot acceptance testing.

5.8.8.1 Approach. This multi-lot method assumes either a normal or lognormal population distribution and uses small sample mean and standard deviation data to estimate the individual lot distributions and in turn to estimate the multi-lot radiation stress end-point limits. One-sided tolerance interval methods are used to estimate the multi-lot distributions related to the desired survivability. Samples to provide the necessary parametric data may be drawn from inspection lots, diffusion lots, wafer lots or even from individual wafers depending upon the known or assumed homogeneity of the sampled population. Typically, lot data are combined to account for differences between vendors and variations from lot-to-lot of a given vendor. Lot sample data from all anticipated sources and from different lots within each source should be included for a thorough assessment.

5.8.8.2 Guidelines and caveats. The basic approach is to utilize multiple-lot sample data to compute reasonable parameter failure limits for pass/fail criteria applicable to attributes lot acceptance testing. These failure limits can also be used as design limits provided that suitable caution is used to account for the statistical basis of these limits. Lot sample data are assumed to be in the form of means and standard deviations of radiation-induced parameter values or parameter delta values (i.e., the difference between post- and pre-irradiation values). Sample sizes are assumed to be small for cost efficiency reasons, typically on the order of 5 to 15. The basic problem then is to combine the means and standard deviations for lot sample data in such a way as to define a "failure" limit or end-point limit from these data. The following guidelines and caveats must be taken into consideration for multi-lot assessments:

a. The data should be in the form of parameter measurements on each part. The parts should be identified with respect to manufacturer, part number and lot number. In some cases, the data may have to be recast into standard bias conditions and standard stress levels. If interpolation procedures have been used for recasting, they must be validated. If extrapolation procedures have been used, further justification may be required.

b. As much peripheral information as possible should be obtained from the vendor. For example, it is advisable to know if the inspection lot is composed of single or multiple diffusion or wafer lots.

c. Check the data carefully for devices in each inspection lot which may be outliers. If outlying devices or lots are found, an explanation should be looked for. Typical causes for outlying measurements are abrupt failure, measurement errors and radical deviations from the assumed probability distribution. In the case of outlying devices in an inspection lot, a typical cause of deviation from lognormality is a lot which is really a mixture of several diffusion or wafer lots. If parameter end-points are being determined from data taken at only one stress, the possibility of abrupt failure must be determined to be negligible.

d. There should be at least five good measurements in each inspection lot and the standard deviation of the parts within an inspection lot should not be more than about 25 percent of the standard deviation representing the lot-to-lot variations. If the within-lot standard deviation is less than 10 percent of the lot-to-lot variations, then the requirement for five good measurements may be relaxed. This is a matter of judgement.

e. Some attempt should be made to verify that the data do not contradict the assumed probability distributions for within-lot variations and for lot-to-lot variations. Almost always, the distributions are assumed normal or lognormal but these assumptions can be in error. Once again, if the variations of parts within a single lot are small compared to the variations between lots, the exact within-lot distribution is less critical.

f. If a common end-point is to be determined for devices from several vendors, special cautions are necessary. Often the major source of variation is from vendor to vendor. In such cases, all the devices from the same vendor might be considered as coming from a single inspection lot. All of the precautions and judgmental decisions mentioned above would apply. It is not recommended that a single end-point include different vendors unless it is established that the parts from one vendor to another are not significantly different. If the major variations are noted to be between manufacturers, then the sample size applied in calculations must be the number of manufacturers and not the number of lots.

g. If the end-points are to be used for design purposes, still further cautions are necessary. There may be simulation fidelity problems arising from discrepancies between the test circuits and test conditions and the actual circuits and actual conditions. Systematic variations in part manufacture over time may be important. Data should be checked for such variations. It is generally recommended that data for end-points encompass a part production time span of at least three months. In any event, predictions of part performance may be compromised if there is a gap of a year or more between qualification data collection and procurement of the production parts.

h. If there is not enough data left after discarding bad data or if the within-lot standard deviation is comparable to the lot-to-lot variations, more complex procedures may be employed though confidence in the results may be lacking. It may be necessary to start anew with procurement restrictions on the source(s) and production runs.

5.8.8.3 Lot quality. Lot quality is typically verified by performing a radiation test on a sample of parts with the requirement that no more than a certain number of failures may occur. One recommendation is that 11 parts be tested from each lot with no failures allowed, an 11/0 test which corresponds to 20 percent failure with 90 percent confidence if overtesting is not used. End-point limits for each device parameter of interest are determined based on the criterion that a given fraction, P_a, of future lots will pass an 11/0 test with 90 percent confidence. The analysis here is performed with the assumption that the parameters follow a normal or (more likely) a lognormal population distribution. The technique may be modified for cases where another distribution is known to govern the parameters.

5.8.8.4 Statistics. In an alternative statement of the problem, for an 11/0 test, the end-points are selected so that, with 90 percent confidence, at least the given fraction, P_a, of future lots will have 99 percent of the parts in the lot passing the test. The rationale for choosing 99 percent is that such a percentage corresponds to about 90 percent probability of having no failures out of 11 tested parts -- more precisely, $(0.99)^{11} = 0.895$. The end-points are then computed by determining a best estimate of a limiting point where 99 percent of the parts for each of N lots will pass the test. If x is the critical parameter of interest,

$$x_{Li} = x_i + 2.326\, s_i$$

for parameters which increase or decrease with radiation, where x_{Li} is the end-point limit for the i^{th} lot, x_i is the mean value of x, and s_i is the standard deviation. (The factor 2.326 arises from the fact that 2.326 standard deviations above the mean of a normal distribution includes 99 percent of the distribution.) For the more usual case where the post-irradiation parameter follows a lognormal distribution, x would represent the logarithm of the parameter. A typical example of the parameter, x, would be the logarithm of the change in reciprocal gain, $\log[\mathrm{delta}(1/h_{FE})]$.

5.8.8.5 End-point. If a sufficient number of parts are sampled from each lot, the values of x_L are approximately distributed according to a normal law. The end-point limit, X_{LL}, for the part type is then determined from the point where with 90 percent confidence, at least a certain fraction, P_s, of future lots will have values of X_L bounded by X_{LL}. The end-point, X_{LL}, is given by the formula:

$$X_{LL} = x_L + K_{TL}(N_L,\ P_s,\ C = 90\%)s_L$$

where N_L is the number of lots, x_L is the mean for the N_L lots, and s_L is the standard deviation for the N_L lots. The function K_{TL} is the one-sided tolerance limit. Appendix table IX presents values for K_{TL} for various values of N_L, P_s, and C. The validity of this multi-lot method has been checked against actual test data and is considered to be sufficiently accurate for most system applications.

5.8.9 Lot acceptance testing (LAT). The following guidelines apply to LAT (see table II):

a. LAT must be performed on all HCC-1M electronic pieceparts procured for production equipment.

b. Piecepart types classified as HCC-2 do not require LAT. However, it is recommended that a sample test be conducted at least once each six month period, and after any manufacturing change as a stability check.

c. Piecepart types classified HCC-1S do not require LAT. However, because of the lack of systems control of manufacturing processes, it is recommended that occasional sample testing be performed similar to that for HCC-2 as a stability check.

5.8.9.1 Definition of lot. The usual terminology applied here is production lot acceptance testing, or quality conformance inspection, though the term "lot" may be somewhat ambiguous. Variations in systems acquisition processes affect the timing and procedures for piecepart acquisition and must be factored into the parts buy and lot definition by the contractor. A very sensitive device (i.e., small but acceptable DM) may require that a lot be the manufacturer's processing, diffusion or single wafer lot, possibly with special controls and traceability. A less sensitive device may require only that the lot be an inspection or fabrication lot (which may consist of several diffusion lots). For even less sensitive devices, a lot may consist of whatever happens to be received as the result of an order. A production lot definition is provided in MIL-I-38535, appendix A, though it should be kept in mind that for devices requiring special controls, the various semiconductor vendors may interpret procurement specifications differently. It is recommended that any special lot procurement requirements be directly coordinated with the manufacturer to assure a mutual understanding of the requirements.

5.8.9.2 Lot handling. Lots procured under these special conditions and destined for LAT must be held under controlled conditions until acceptance tests are performed and lot disposition determined. Contingency plans should be formulated for possible failed lots. Such plans would include consideration of possible further 100 percent electrical screens of the lot to truncate the distribution, followed by a second lot acceptance test (or if an attributes method is being used, selection of an additional sample for the LAT with an allowable failure rate for the increased sample size).

5.8.9.3 Lot failure. It is important to remember that failure of a lot sample means rejection of the entire lot. If a large fraction of the lots (comparable to the desired confidence level, C) is rejected, then it is likely that even those few lots which passed the lot acceptance tests are also unacceptable. In such a case, consideration should be given to looking for an alternate vendor source or part type, and/or to circuit redesign.

5.8.9.4 Test data. LAT requirements must be derived from the radiation data acquired in the piecepart qualification program. In addition to being used for determining the R_{FAIL} values, the shape of the data plots is evaluated to determine if the LATs should be a single dose type test at the radiation specification level, or multiple irradiation to failure (variables) type test. If the data plots are approximately log-linear (for a lognormal cumulative probability distribution) the lot acceptance test(s) may be performed with a single exposure at the specification level. However, if the shape of the data plots varies significantly from the log-linear, multiple irradiation to failure is preferable. Occasionally, when characterization tests are conducted, not all of the parameter values will reach PAR_{FAIL}, even when the radiation levels are much higher than the specification level. In this case, as an engineering judgement, a minimum of five test parts should reach PAR_{FAIL} if the test is to be meaningful for a radiation based assessment (section 5.6). The full details of lot acceptance test requirements must be developed and included as a part of each piecepart procurement package. Details must be provided on electrical test configuration(s) and radiation environments as well as any special considerations, such as temperature. Sampling method, sample size and selection procedures, and LAC must be specified.

5.8.9.5 Lot acceptance testing methods. Selection of the LAT procedure, whether variables or attributes , must be an engineering trade-off related to cost, parts availability, system requirements, operational maintenance engineering and test capabilities, etc. Two major trade-offs to consider are test sample size and data analysis capabilities. Sample sizes for attributes testing are typically larger, and often much larger than required for the same statistical levels determined through variables testing. The cost of the pieceparts, particularly where large samples are concerned, is a most important consideration. In addition, the piecepart's availability can also be important: e.g., if it is a low yield product, adequate sample parts may not be available. The system's parts procurement procedures can also be important; that is, are parts procured for the full system buy at one time, or are there procurements at intervals during production? Attributes testing is a go/no-go test that requires no further engineering evaluation of the data. Variables testing, however, requires further engineering time to reduce and evaluate the test data for lot acceptance or rejection. The operational maintenance organization may have a preference in procedures related to their capabilities in both testing and engineering.

5.8.9.6 Lot acceptance criteria (LAC). Recommended procedures for specifying LAC are based on data derived from the pieceparts qualification program. Where LAT involves more than one critical parameter, a criterion for lot acceptance must be developed for each parameter. The following sections address the statistical methods used for calculating LAC and their application to both the variables and attributes methods.

5.8.9.6.1 LAC for variables testing. Since both the sample mean and standard deviation will vary from lot to lot, each lot sample must be assessed for each critical parameter by the same procedure as that applied to the qualification data. The LAC for a lot sample will be based on the piecepart level P_s and C and the sample size, n, applied to the one sided tolerance tables to determine the LAC value. Lot acceptance decisions are made by requiring that the DM for the lot be greater than the LAC for that same lot.

The LAC are as follows:

Lot is acceptable if:

for radiation based comparison,

$$RDM(LOT) = e^{\frac{\overline{[\ln(R_{FAIL}), LOT]}}{R_{SPEC}}} \geq e^{[K_{TL}s_{\ln}(R_{FAIL}), LOT]}$$

for parameter based comparison, increasing parameter values,

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

for parameter based comparison, decreasing parameter values,

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

5.8.9.6.2 LAC for attributes testing. The LAC for attributes testing is composed of two essential parts, the attributes statistical requirements and the piecepart PAR_{FAIL} value. The attributes tables set the test sample size and acceptable failure rate for a given survivability and confidence level. Table B-1, appendix B of MIL-I-38535, appendix A provides the sampling requirements for 90 percent confidence for various survival levels. These survival levels are given as maximum allowable percent defective. That is, if a 90 percent survival rate is required, the 10 percent maximum percent defective column is appropriate. The PAR_{FAIL} value is the failure criterion on which lot acceptance or rejection is based. The PAR_{RAD} value for each part in the test sample, following irradiation, is compared with the PAR_{FAIL} value to determine if it passed or failed the test. If the failure rate of the test sample exceeds the acceptance number given in the attributes table, the lot is rejected. Where a piecepart has more than one critical electrical parameter, each individual parameter PAR_{FAIL} value is a criterion for lot acceptance.

5.8.9.6.2.1 Example. If any parameter fails the lot acceptance test, the lot is rejected. For the attributes method, the piecepart sample is tested at a single radiation level (typically, the specification level). As an example, using the table B-I, MIL-I-38535, appendix A, appendix B, for a P_s = 90 percent and C = 90 percent, no failures are allowed for a sample of 22 devices and one failure is allowed for a sample of 38 devices.

5.8.9.6.2.2 Using overtesting. An overtest procedure will be described later which involves testing at a radiation level higher than the specification level. This makes it possible to reduce the sample size for the specified survival requirements or to determine a higher survival probability for a given sample size.

5.8.10 Procurement lead time. Piecepart procurement lead time must be taken into consideration for both test samples and production lots. Many MIL-STD and special vendor pieceparts require a year lead time to delivery. This alone can play havoc with test and production schedules. In addition, qualification or lot acceptance failures can exacerbate the problem. Contingency plans should be developed outlining procedures to be followed for situation where lot failures can affect production schedules.

5.8.10.1 Time-savers. Often, a cost effective method, particularly for parts requiring special vendor controls, is to arrange with the parts vendor to obtain early packaged samples from the production line for radiation testing. This should be done immediately after dicing, with the remaining die held in storage until the results of the radiation lot acceptance tests are known. Failed lots may then be diverted to nonradiation usage without extra cost to the project: replacement lots may then be started through the line. Another similar approach is to perform "on-line" wafer level sample testing for ionizing dose. This may involve the use of an x-ray wafer-level irradiator such as produced by ARACOR Corporation (see 6.48). In this approach, selected die on a wafer are irradiated at a probe station to a given dose level, or in step levels, and device response characteristics are measured and evaluated against specified LAC. The ARACOR on-line tester operates at a lower energy spectrum (approximately 10 keV) than cobalt-60 test facilities (approximately 1 MeV), and damage correlation factors between the environments must be developed (see 6.54).

5.8.11 Sample size criteria. Sample size may be affected by such things as: whether the testing is for qualification or lot acceptance, the availability of existing data and the indicated part's susceptibility, whether the initial sample data appears well behaved, radiation specification levels, survival requirements, parts costs, test complexity and the form of testing, and whether the variables or attributes method is to be used. Although a small sample size reduces the cost of characterization testing, it will increase the uncertainty in knowledge of the part's distribution. It should be kept in mind that the selection of a larger sample size during qualification testing may better characterize the device and eliminate the need for expensive lot acceptance testing of production parts. The primary trade-off is between the cost of characterization testing for qualification (which may establish a part as HCC-2 rather than HCC-1M) and the relatively high cost of lot acceptance testing for HCC-1M pieceparts. Sample size must be a trade-off between these various factors though the final results must show an adequate confidence in the parts survivability.

5.8.11.1 Makeup. A nominal sample size of 10 devices per lot is a typical starting point for most variables data whether applied to qualification or lot acceptance testing. The sample should include devices from more than one production lot in order to assess multi-lot variability. Also, if multiple vendors are supplying the piecepart, the sample should include devices from each vendor. Traceability should be maintained of all pieceparts in the sample in the event that a portion of the sample from a particular vendor or lot proves exceptionally vulnerable. Traceability permits feedback to the vendor that can result in tighter production controls and less susceptible pieceparts. Multi-lot data may increase the data spread making data interpretation difficult and requiring use of the maximum sample size discussed below.

5.8.11.2 Suggested sample sizes. Table II provides both minimum and maximum recommended lot sample sizes for variables testing applicable to either qualification or lot acceptance testing. (The sample size for attributes testing is dictated by the attributes tables.) The interpretation of the sample size of 10 to 30 is that the basic (and minimum) sample size is 10, and if the data are widely scattered, or difficult to interpret, then an additional sample of 20 may be tested to make a total sample of 30 pieceparts. The given maximum sample sizes are for purposes of assessing the data viability: larger sample sizes may certainly be used. If the larger sample still presents interpretation problems, the piecepart should be reevaluated for acceptability. A similar interpretation applies to the table sample size values of 5 minimum and 10 maximum. A minimum sample of 5 pieceparts is indicated where the established DM is relatively large and should generally be considered the minimum sample size for data having statistical significance.

5.8.12 RHA devices. Note that Radiation Hardness Assured (RHA) devices are indicated for systems application in table II. RHA devices should be accepted by the Government as hard to the M, D, E, R, F, G, or H levels as specified in MIL-I-38535, and MIL-S-19500. If the RHA devices are used in keeping with any derating (if specified in the slash sheet for each device type), then no further qualification or lot acceptance testing is required of the contractor. A primary objective of the RHA program is to eliminate costly redundant testing of commonly used devices by multiple contractors.

5.8.13 Combining data. To increase the effective sample size and achieve a better characterization of a given device, it is desirable to combine the data from various tests of the identical part type. The combined data can greatly increase the confidence that can be placed in the test results. When sufficient data have been accumulated on a particular part type, the part type characteristics and Hardness Critical Categorization (HCC) should be reevaluated. It may, for example, be possible to reclassify the part for less stringent procurement and testing requirements. Caution should be used in establishing the identical nature of the parts used in the different tests. It should be kept in mind that the same nomenclature part type from different vendors may have considerably different radiation responses. In addition, the test procedures, including bias conditions and radiation environments, must be correlated. If the piecepart procurement requirements do not limit procurement to a particular vendor, then data for different vendors should be maintained separately in the event of failure problems which may be identified with a particular vendor.

5.8.14 Combined environments damage. For most system design cases, piecepart response is considered independently for each specified radiation environment: samples are tested in each environment and design margins and categories are developed for each piecepart type for each environment. For cost effectiveness, pieceparts are sometimes irradiated at a nuclear reactor where, with selective shielding, they concurrently acquire the desired neutron fluence and ionizing dose. Often, the technology of the devices is indicative of the environment (neutron or gamma) producing the greatest damage. For example, MOSFETs are relatively insensitive to neutron damage but may be very sensitive to ionizing dose. This form of response testing may be treated in accordance with the categorization rules for the environment judged to be producing the most significant damage. That is, the HCC guidelines and typically computerized HCI listings (see reference 6.30) do not address combined environments so the HCC is listed under the environment producing the greatest damage.

5.8.14.1 Analysis procedures. For the opposite case, where testing is performed independently and it is desirable for a particular system to work with a combined environments approach, three procedures are outlined below: 1) directly additive; 2) relative percent or factor; and 3) Root-Mean-Square (RMS). Each of these approaches has been used to some extent.

5.8.14.1.1 Additive. The directly additive approach is the most straight-forward in that the parameter change resulting from the specification neutron fluence is summed with the parameter change induced at the ionizing dose specification level to give a combined damage parameter value. Such a summation may be taken at the parametric mean value point or at a selected point on the distribution (e.g., 3s) as a worst case limit. For example, separate transistor samples were tested independently at neutron and gamma sources and had mean values (or values taken at some factor times the standard deviation) of an initial gain of 80, a gain of 60 following neutron irradiation and a gain of 70 following gamma irradiation. The additive combined damage would result in a gain of 54. This approach satisfies the requirement that the system independently survive each environment.

5.8.14.1.2 Relative percent. The relative percent or factor approach may be applied when one of the radiation environments is of a low level and the other is of a significant level. This is an engineering judgement approach to reduce work and associated costs. In this case, an additional percentage of the significant-environment damage is assumed to account for any small changes induced by the low level environment. For example, if the ionizing dose specification is significant but the neutron specification is quite low, an additional ten or twenty percent of the ionizing dose induced parameter change may be added to account for any small amounts of damage induced by the neutron fluence, thus eliminating the need to test in the neutron environment.

5.8.14.1.3 RMS. The third approach is the RMS method that may be applied to pieceparts for the determination of end-point electrical parameters for multiple radiation environments (see 6.55). (This procedure may also be applied to delta parameters, i.e., initial parameter value minus the radiation induced parameter value.) In this case, the individual end-point limits for each environment are combined in a valid approximation to determine the resultant part characteristics.

5.8.14.1.3.1 Normal example. This approach is outlined in the following equations for the case where the parameters are normally distributed. If the two environments act on the device in an uncorrelated way, the approximate end-point limit for a normally distributed combination of the two environments is:

$$X_{LLC} = PAR_{MFn} + PAR_{MFg} + \sqrt{[K_{TLn}S_n]^2 + [K_{TLg}S_g]^2} \qquad \text{Eq. 5.8.10-1}$$

where:

X_{LLC} is the combined limit for parameter PAR,

PAR_{MFn} and PAR_{MFg} are the respective arithmetic means for the neutron and ionizing dose environments,

K_{TLn} is the one sided tolerance limit factor for the neutron sample,

K_{TLg} is the one sided tolerance limit factor for the gamma (ionizing dose) sample,

s_n and s_g are the respective standard deviations for the neutron and ionizing dose environments.

5.8.14.1.3.2 Lognormal example. For the lognormal case, the log values of the parameters are used to calculate the respective means and standard deviations to apply to equation 5.8.10-1. The antilog is then taken, i.e.,

$$e^{(X_{LLC})}$$

to determine the combined end-point limit.

5.8.14.2 Difficulties. These approaches do not address questions of synergism, antagonism, or nonlinearity with varying initial conditions. That is, whether damage from the combination of environments results in more, less, or the same damage as determined when tested independently or whether the net damage is the same with neutron testing performed first followed by ionizing dose testing as compared with the testing order reversed or with concurrent irradiations. These, however, are usually second order effects that produce negligible differences in measured values.

5.8.15 Overtesting. Overtesting (see 6.56) consists of testing a sample of parts at a stress level higher than the specification stress level with statistical interpretation of P_S at the stress level. This approach will reduce the sample size that must be tested to meet a given quality acceptance standard at the specification level. The overtest approach is intended primarily to apply to sampling by attributes (reference 6.40).

5.8.15.1 Appropriateness. Overtesting is an appropriate technique to apply when:

a. Testing of variables is impractical because of time and cost considerations, or because the probability distribution of stress to failure cannot be estimated with sufficient accuracy, or

b. An unrealistically large number of parts would have to be tested at the specification stress for the necessary confidence and survival probability.

5.8.15.2 Probability distribution. In overtesting, a knowledge of the probability distribution governing stress-to-failure is required, though it need not be specified with the same accuracy necessary for testing by variables. Typically, a lognormal distribution is assumed for both neutron and ionizing dose damage in electronic pieceparts when no better distribution assumption has been derived from the test data. However, caution should be exercised when the probability distribution is not well established. Nevertheless, even if the lognormal distribution does not strictly apply, the formulas given below will hold as long as a sufficiently conservative estimate is made of the variability of the parts within the stress range of interest.

5.8.15.3 Overtest formulas. Let R_T and R_S be the respective radiation overtest and specification stress levels. Let ln(max) be an estimated maximum standard deviation in the natural logarithms of the stress to failure, and let P_T and P_S be the respective survival probabilities with confidence, C, at the overtest and specification stress levels. Then,

$$P_S = F[\overline{F}(P_T] + \frac{\ln(R_T/R_S)}{\sigma_{\ln}(\max)} \qquad \text{Eq. 5.9.1-1}$$

where F is the cumulative standard normal distribution and $\overline{F}$ is its antifunction. When P_S is given and P_T is desired, the overtest factor is:

$$\frac{R_T}{R_S} = e^{\sigma_{\ln}(\max)\,[\overline{F}(P_S)-\overline{F}(P_T)]} \qquad \text{Eq. 5.9.1-2}$$

5.8.15.4 Overtest example. Suppose that bipolar transistors are tested to three times the specification fluence and it is determined that with 90 percent confidence, at least 80 percent of the transistors will survive the overtest fluence. For bipolar device neutron damage, 0.5 is used as a good estimate of ln(max). Then, from equation 5.9.1-1, at the specification fluence, with 90 percent confidence, the survival probability is:

$$P_S = F[\bar{F}(0.8) + (\ln 3)/0.5] = F[0.84 + 2.20] = 0.999.$$

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STATISTICAL TECHNIQUES FOR HARDNESS ASSURANCE

10. GENERAL

10.1 Scope. This appendix details statistical techniques that are used in hardness assurance.

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. STATISTICAL TECHNIQUES FOR HARDNESS ASSURANCE

50.1 Basic concepts. This appendix concentrates on statistical techniques which are used in hardness assurance. Standard texts on general statistics are recommended to amplify the subject:

a. Sections 60.1 and 60.2 for basic concepts

b. Section 60.3 for industrial quality control

c. Section 60.4 for statistical techniques in data analysis

d. Section 60.5 for a complete guide to statistical analysis

e. Sections 60.6 and 60.7 for the statistics of sampling and quality control

50.1.1 Discrete probabilities. Discrete probabilities occur whenever there is a denumerable set of outcomes from an experiment. The probability can refer to an attribute (for example, the probability of picking a red ball out of a bag of red and white balls) or to a value (for example, the number of radioactive disintegrations in a Co-60 source occurring in one second, or the number of grains in one pound of sand). It is customary to define the probability of the i^{th} possibility as

P_i = Probability that the i^{th} possibility will occur Eq. 50.1-1

and,

$$\sum_i P_i = 1 \qquad \text{Eq. 50.1-2}$$

It is also customary in standard texts to use q_i for the probability that the i^{th} possibility will not occur.

$$q_i = 1 - P_i \qquad \text{Eq. 50.1-3}$$

The discrete probabilities which occur most frequently in hardness assurance are the ones where there are two possible attributes - survival and failure

P_S = Probability that a part will survive Eq. 50.1-4

and

P_F = Probability that a part will fail Eq. 50.1-5

50.1.2 Continuous probability distributions. Clearly the limiting case of a discrete probability distribution where alternatives may be assigned numerical values (for example, the number of radioactive disintegrations of a Co-60 source) is the continuous distribution.

50.1.2.1 The probability distribution function (PDF). The probability distribution function gives the probability that a randomly distributed value x will be between the limits x and x + dx, where dx is an infinitesimal increment. This is illustrated on figure 10.

f(x)dx = Probability that x is between x and x + dxEq. 50.1-6

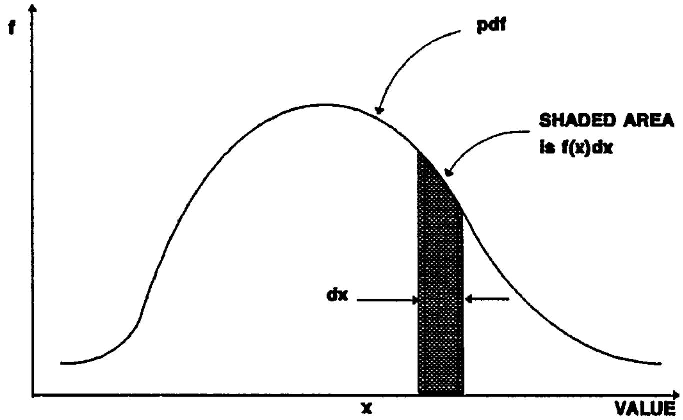

FIGURE 10. Probability distribution function.

50.1.2.2 The cumulative distribution function (CDF). The cumulative distribution function is the probability that the variable x will be less than the value X.

$$F(X) = \text{Probability that } x \leq X \int_{-\infty}^{X} f(x)\,dx \qquad \text{Eq. 50.1-7}$$

The meaning of F(X) is illustrated on figure 11.

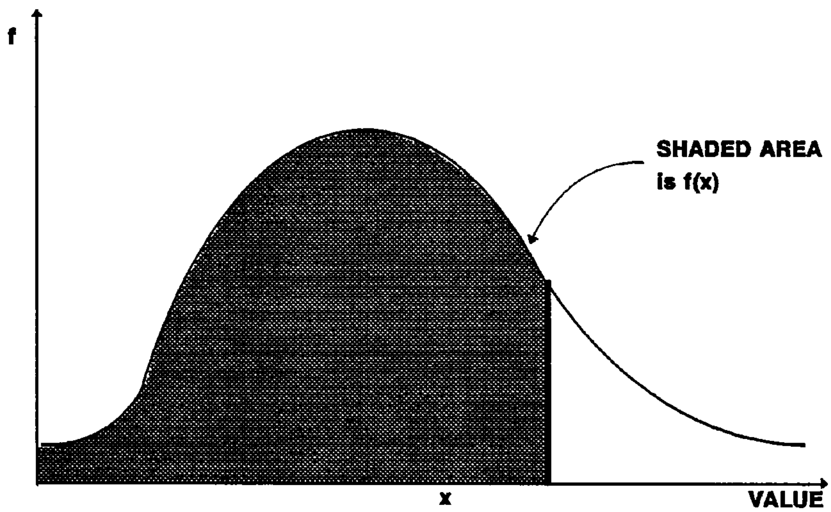

FIGURE 11. Cumulative distribution function.

50.1.3 Means and standard deviations. Every probability distribution is characterized by a mean, μ, (usually the arithmetic average of the sample data points) and a standard deviation, σ (which is a measure of the distribution dispersion about the mean). The variance is simply the square of the standard deviation, σ^2.

50.1.3.1 Discrete distribution. When the characteristic being measured can take on only specific values (e.g., integers, 0, 1, 2, etc.) the probability distribution is called a discrete distribution. For discrete distributions where the different possibilities refer to numerical values, x_i, and where there are N possibilities, the theoretical mean and variance are represented by

$$\text{mean,} \quad \mu = \sum_{i=1}^{N} x_i P_i \qquad \text{Eq. 50.1-8}$$

and

$$\text{variance,} \quad \sigma^2 = \sum_{i=1}^{N} (X_i - \mu)^2 P_i \qquad \text{Eq. 50.1-9a}$$

which is equivalent to (see 60.1)

$$\sigma^2 = \sum_{i=1}^{N} X_i^2 P_i - \mu^2 \qquad \text{Eq. 50.1-9b}$$

50.1.3.2 Continuous distributions. When the characteristic being measured can take on any value (integer or fraction) within the physical limits of the characteristic, the probability distribution is called a continuous distribution. The general expressions for the mean and variance for continuous distribution are given by

$$\text{mean,} \quad \mu = \int_{-\infty}^{+\infty} X f(x)\, dx \qquad \text{Eq. 50.1-10}$$

and

$$\text{variance,} \quad \sigma^2 = \int_{-\infty}^{+\infty} (x - \mu)^2 f(x)\, dx \qquad \text{Eq. 50.1-11a}$$

which is equivalent to

50.1.3.3 Means and standard deviations for a measurement. When the outcome of an experiment is a numerical value and when n items have been sampled from either a discrete or a continuous distribution, these n values give measured

$$\sigma^2 = \int_{-\infty}^{+\infty} x^2 f(x)\, dx - \mu^2 \qquad \text{Eq. 50.1-11b}$$

estimates of the true mean and standard deviation. These estimates are denoted here by the symbols m and s respectively.

$$m = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad \text{Eq. 50.1-12}$$

$$s^2 = \frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - m)^2 \qquad \text{Eq. 50.1-13a}$$

$$s^2 = \frac{1}{(n-1)} \sum_{i=1}^{n} (x_i^2 - nm^2) \qquad \text{Eq. 50.1-13b}$$

(The substitution of n-1 for n in the variance equations corrects for the consistent tendency to underestimate the variance for small sample sizes (see 60.2).)

50.2 Some specific probability distributions. This section will be concerned with certain continuous distributions which occur frequently in sampling measurements. By far the most important of these for semiconductor response are the normal and the lognormal distributions. Other distributions will be mentioned because they are occasionally applicable and because the circumstances under which they might be used must be included in a complete discussion.

50.2.1 The normal distribution. The normal distribution is the one which occurs most frequently in probability theory. The probability distribution function for a normal distribution with a mean, μ, and standard deviation, σ, is

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-[\frac{(x-\mu)^2}{2\sigma^2}]} \qquad \text{Eq. 50.2-1}$$

50.2.1.1 Features. Normal distributions have the unique property that if any number of random variables are sampled from any number of different normal distributions, the probability distribution of their sum is also a normal distribution. The importance of the normal distribution is a result of the central limit theorem (described in most standard texts) which states that the sum of n independent random variables has an approximately normal distribution when n is large. The approximation becomes exact as n approaches infinity. The normal distribution arises therefore in any situation where the desired quantity is due to the combined effect of a large number of random variables regardless of the specific probability distribution which may apply to these variables. Practically all random walk problems, for example, result in normal probability distributions after a sufficiently large number of steps have been made.

50.2.1.2 Standard normal distributions. By a linear transformation of variables, any normal distribution may be expressed as a normal distribution with a mean of zero and a standard deviation of unity. The probability distribution function for a standard normal distribution is

$$f_n(x) = \frac{1}{\sqrt{2\pi}} e^{-[\frac{x^2}{2}]} \qquad \text{Eq. 50.2-2}$$

The cumulative standard normal distribution is

$$F_n(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-[\frac{x^2}{2}]} dx \qquad \text{Eq. 50.2-3}$$

50.2.1.3 Tabulations for the normal distribution. Most standard texts and statistical handbooks have tabulations of both the functions f_n and F_n (see 60.1, 60.2, and 60.4). In some cases a transformation of the cumulative function of equation 50.2-3 is tabulated. One excellent tabulation (see 60.8) gives the functions

$$\frac{1}{\sqrt{2\pi}} e^{-[\frac{x^2}{2}]} \text{ and, } \frac{1}{\sqrt{2\pi}} \int_{-x}^{x} e^{-[\frac{x^2}{2}]} dx$$

as a function of x, as x varies from 0 to 7.8. The function $F_n(x)$ may be derived from this second function by the linear transformation:

Some computers and tabulation provide a function called the error function:

$$F_n(x) = \frac{1}{2} + \frac{1}{2}\, erf\left(\frac{x}{\sqrt{2}}\right) \qquad \text{Eq. 50.2.6}$$

for which the function $F_n(x)$ may be derived as

$$erf(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-[x^2]}\, dx \qquad \text{Eq. 50.2-5}$$

50.2.1.4 Measured means and standard deviations for a normal distribution. If n values are sampled from a normal distribution with a mean of μ and a standard deviation of σ then the measured mean, m, follows a normal distribution with a mean of μ and a standard deviation of $\sigma n^{-1/2}$. The quantity $(n-1)s^2/\sigma^2$ is distributed as a chi-squared distribution with n-1 degrees of freedom. This property is sometimes useful for checking the validity of data (see 60.1 and 60.2).

50.2.1.5 Normal probability paper. There exists a graph paper, called normal probability paper, which is very convenient for displaying normally distributed variables (figure 12). This graph paper may be used to obtain a visual check on (a) whether the sample was drawn from a normal distribution, (b) an estimate of the mean of the distribution, and (c) an estimate of its standard deviation.

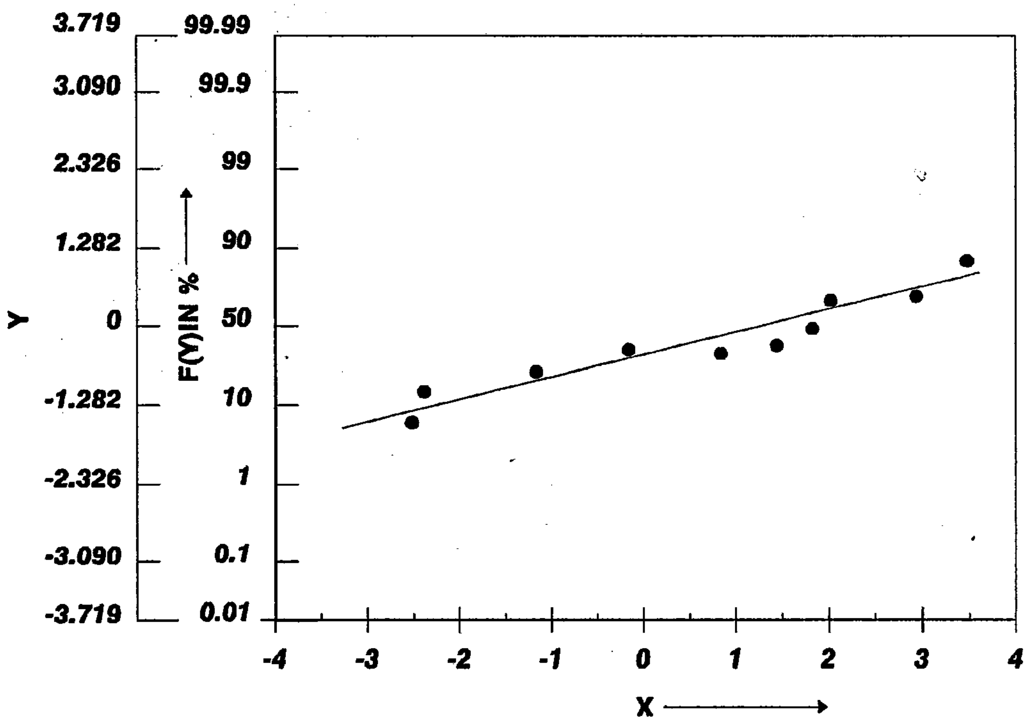

FIGURE 12. Normal probability paper.

50.2.1.5.1 Design and application. On normal probability paper, the ordinate, Y, is labeled with the cumulative probability function $F_n(Y)$, usually expressed as a percent. In general, the center of the ordinate represents $F_n(Y) = 50$ percent (that is, Y = 0 for a standard normal distribution). The paper is used as follows:

a. If n measurements were made of the variable, x, the n values must be ranked according to size such that:

$$x_1 < x_2 < x_3 \ldots x_{n-1} < x_n$$

b. Next to the i^{th} value, x_i, write the number i/(n+1) to get the following list

x_1	1/(n+1)
x_2	2/(n+1)
.	.

.	.
.	.
x_{n-1}	(n-1)/(n+1)
x_n	n/(n+1)

c. The values of x_i, are then plotted along the abscissa against the corresponding values in the second column.

50.2.1.5.2 Example. If the values of x were drawn from a normal distribution, the plot should be a straight line with intercept (intersection with the 50 percent line) approximately equal to the mean of the distribution and with slope, $\Delta Y/\Delta$, which is approximately equal to $1/\sigma$. As an example, consider the following 10 values drawn from a known normal distribution with mean of 1.0 and standard deviation of 2.0:

1.834	-0.0342	3.152	-1.202	1.938
-2.230	-2.098	1.478	0.596	3.564

a. Rank the values according to size

-2.230	-2.098	-1.202	-0.0342	0.596
1.478	1.834	1.938	3.152	3.564

b. Make a table for the plot

x	F(Y)	x	F(Y)
-2.230	1/11=0.0909	1.478	6/11=0.5455
-2.098	2/11=0.1818	1.834	7/11=0.6364
-1.202	3/11=0.2727	1.938	8/11=0.7273
-0.0342	4/11=0.3636	3.152	9/11=0.8182
0.596	5/11=0.4545	3.564	10/11=0.9091

c. Plot the points as shown on figure 3.

50.2.1.5.3 Visual readings. A visual fit of the points gives the intercept with the 50 percent ordinate value at x = 0.7 and the reciprocal slope = 2.4 (i.e., the ratio of the absolute change value of the abscissa to the absolute change value of the ordinate as given in standard deviations). To the noted visual accuracy, these values are the same as would be obtained from equation 50.1-12 and 50.1-13.

50.2.1.6 Analytic tests for normality and outliers. In addition to the visual check described above, the reader is referred to analytic checks that the distribution is truly normal (see 60.9) and to checks for outliers (see 60.10).

50.2.2 Lognormal distributions. A lognormal distribution is one where the logarithms of quantities, x, are distributed normally. The frequency distribution function for the lognormal distribution is (see 60.11):

$$f(x) = \frac{1}{x\sigma_{\ln(x)}\sqrt{2\pi}} e^{-[\frac{1}{2(\sigma_{\ln(x)})^2}(\ln(x)-\mu_{\ln(x)})^2]} \qquad \text{Eq. 50.2-7}$$

where $\sigma_{\ln(x)}$ is the standard deviation in the logarithms of the values of x and $\mu_{\ln(x)}$ is the mean of the logarithms.

50.2.2.1 Occurrence. Lognormal distributions occur in situations where a large number of random numbers are multiplied together. Clearly, if the numbers are randomly distributed, then their logarithms are also randomly distributed. Therefore, when the numbers are multiplied together, the logarithm of the result is the sum of many randomly chosen numbers. By the central limit theorem discussed earlier, the resulting logarithm must be normally distributed.

50.2.2.2 Example. An example of the lognormal distribution taken from nature is the distribution of the sizes of small particles such as particles of sand or soil where the particles were formed from the grinding down of large rocks. The final particle sizes result from a large number of random splittings of the original rock and obey a lognormal distribution. Each splitting can be considered to multiply the fragment size by a random number between zero and one.

50.2.2.3 Application. Because the device damage factors of transistors typically follow a lognormal distribution, (see 60.12), and because this distribution fits many other forms of deterioration due to radiation, (see 60.13) the lognormal distribution is the one which is used almost exclusively in the main text of this document. A more complete discussion of the lognormal distribution may be found in reference 60.11.

50.2.2.4 Logarithmic means and standard deviations. Because the lognormal distribution is so important in radiation damage, some formulas and conventions useful for this distribution will be given. If the variable x is distributed lognormally, the following quantities are defined:

$$\textit{Measured logarithmic mean} = \overline{\ln(x)} = \frac{1}{n}\sum_{i=1}^{n} \ln(x_i) \qquad \text{Eq. 50.2-8}$$

$$\textit{Meas. log. variance} = S^2\ln(x) = \frac{1}{n-1}\sum_{i=1}^{n} [\ln(x_i - \overline{\ln(x_i)}]^2 \qquad \text{Eq. 50.2-9}$$

50.2.2.5 Lognormal probability paper. Lognormal probability paper is exactly the same as normal probability paper except that the abscissa is a logarithmic scale.

50.2.3 Other probability distributions. A number of other probability distributions which arise frequently in quality control will briefly be mentioned here together with references to detailed discussions. As is true for the normal lognormal distributions, most of these other distributions have an associated specific probability paper.

50.2.3.1 Chi-squared distributions. If n variables are sampled from a standard normal distribution, then the sum of their squares will be distributed as a chi-squared distribution with n-1 degrees of freedom. These distributions occur most frequently in assigning a confidence to a measured standard deviation and in testing whether a hypothetical statistical distribution is consistent with measurements. Table A-3 in 60.4 gives a cumulative distribution function for the chi-squared distribution as a function of the degrees of freedom.

50.2.3.2 Exponential distribution. This distribution is frequently used to describe the time between failure of a repairable device or system (or alternatively the time to the first failure for a system which cannot be repaired). A good discussion of this distribution and its applications is given in 60.3.

50.2.3.3 Weibull distributions. This is a family of distributions which includes all exponential distributions as well as a close approximation to the normal distribution. It is often used for fitting an empirical probability distribution to a set of data. With three adjustable parameters, the Weilbull distribution can be used to fit truncated distributions. A good discussion of Weibull distributions is given in 60.3.

50.2.3.4 Extreme value distributions. Extreme value distributions are the distributions of the largest or the smallest values in a set of randomly selected items or the largest or smallest values over periods of time. Examples are (a) the distribution of the heights of men, each of which is the tallest out of a group of 100 men, or (b) the distribution of the peak temperatures for each year over a period of many years. In statistics, such distributions are often applied to the analysis of outliers. In nature and in economics they are applied to the analysis of unusual (sometimes disastrous) situations such as heat waves, cold snaps, floods, droughts, depressions and so forth. In quality control, such distributions can be important when a system consisting of many parts will fail if even one of the parts fails. In such a case, the probability distribution for failure is the distribution of the weakest out of n parts, where n is the number of parts in the system. Further discussions of extreme value distributions may be found in 60.4 and 60.5.

50.3 Sampling. The aim of sampling is to predict the behavior of a large number of items on the basis of measurements made on a small sample of those items. Most frequently, the results are reported in terms of a confidence, C, that at least a proportion, P, of the lot will fail under actual use.

50.3.1 Basic types. There are two basic types of sampling techniques - sampling by attribute and sampling by variables. In sampling by attribute, some property of the item is observed, for example a color. Usually there are only two attributes as for example, the item survival or failure under test conditions. In sampling by variables, a measurement is made of some critical parameter for a number of devices and this measurement is compared with a known or approximate probability distribution to determine the confidence, C, and probability, P, that the parameter will not exceed a certain value. In general, sampling by attribute has the advantage that it does not require any assumptions about the probability distribution governing the failure of the devices. However, attributes methods usually require the testing of a very large number of devices before a high probability of survival for individual devices can be predicted. Sampling by variable requires fewer test devices, but has the disadvantage that assumptions must be made about the probability distribution of the measured parameter. Such assumptions are generally reasonable. However, when extremely low failure rates are required, any small deviations from the assumed probability distribution at the extremes of the distribution, can be very significant. Both techniques will be discussed in this section with emphasis on the technique of sampling by variables.

50.3.2 Caution. A note of caution must be interjected here. Most of the sampling techniques report with a given confidence the probability that a bad lot will be rejected by a test rather than the probability that a defective lot will be accepted. We may assume that the same bad lot rejection technique holds true for defective lot acceptance, which may be the case under most reasonable circumstances. However, it is easy to imagine cases where it would not work. For example, suppose that all the lots of a certain manufacturer were defective. Even the few lots which passed an acceptance test by chance would still be substandard, and it would be quite incorrect to suppose that the accepted lots met standards with a high degree of probability. Thus, whenever a large fraction of the tested lots is rejected, (a fraction approaching the confidence C) all of the lots should be suspect. Further discussions of sampling plans are given in 60.3, 60.6, and 60.7.

50.3.3 Sampling by attribute. In a typical sampling by attribute plan, a sample size, n, is chosen from a lot of size, N, and the number of failures is determined. If the number of failures exceeds a certain acceptance number, c, then the lot is rejected. 60.14 gives tables which are used for performing the attributes test. For these tables, any lot with more than the listed percent defective stands more than a ninety percent chance of being rejected. It should be noted that in the table in 60.14, the percent defective refers to the lot before the test was performed. If the tested parts are not returned to the lot (for example, a destructive test), then the test itself influences the percent defective in the remaining lot. For small lots, this effect may be significant. Usually, when very high lot qualities are desired, the attributes method requires an enormous number of parts. However, in some cases, there may be an extensive past history of how a device responds under use and, therefore, data for such a large number of tested parts may exist.

50.3.4 Sampling by variable - one sided tolerance limits. If a parameter is known to be normally distributed, then estimates of lot quality can be obtained with perhaps as small a number of items as ten. If the parameter, x, is normally distributed and n items are sampled, a lot is rejected if the limiting quantity, L, exceeds a value, L_{max}, where (figure 13)

$$L_{max} = m + K_{TL}(n, C, P)\, s \qquad \text{Eq. 50.3-1}$$

where (for a normal distribution) m is the measured mean as determined by equation 50.1-12. The one sided tolerance limit, K_{TL} is a function of the sample size, n, the desired confidence, C, and lot quality, P, such that if more than proportion, P, of the parent distribution has values of x greater than L_{max}, then the lot will be rejected with confidence, C. The limit, L_{max}, is derived from circuit analysis determination of the device change that will induce circuit failure. In some cases, the critical value may be a minimum. In these cases, the lot is rejected if the quantity, L, is less than L_{min} where

$$L_{min} = m - K_{TL}(n, C, P)\, s \qquad \text{Eq. 50.3-2}$$

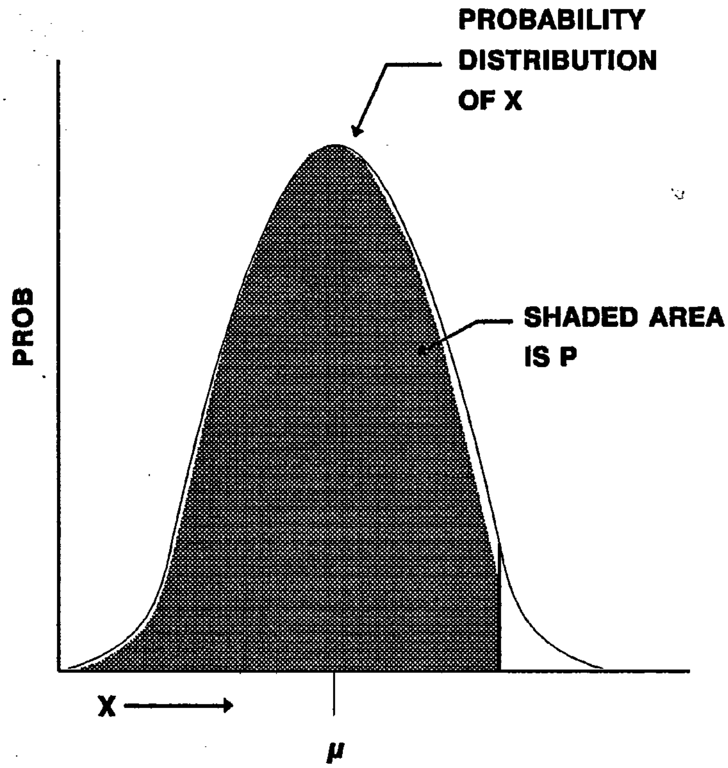

FIGURE 13. One-sided tolerance limit.

50.3.4.1 Tabulations and calculations for one sided tolerance limits. An approximate formula for the calculation of the one sided tolerance limit is given on page 2-15 of 60.4 and more precise values are given in table A-7 of the same reference. Even more precise and more complete tables are given in 60.15; in that reference, values of K_{TL} may be found for values of P up to 0.9999.

Table IX shows values of K_{TL} for some of the most frequently used confidences and lot qualities.

K_{TL} factors such that with confidence, C, at least a proportion, P, of a normal distribution will be less than m + K_{TL}s where m and s are the measured mean and standard deviations respectively. The K_{TL} factors are presented as a function of C, P, and the sample size, n, used in measuring m and s.

TABLE IXA. One-sided tolerance limits K_{TL}

C = 0.75

P

n	0.75	0.90	0.95	0.99	0.999
3	1.464	2.501	3.152	4.396	5.805
4	1.256	2.134	2.680	3.726	4.910
5	1.152	1.961	2.463	3.421	4.507
6	1.087	1.860	2.336	3.243	4.273
7	1.043	1.791	2.250	3.126	4.118
8	1.010	1.740	2.190	3.042	4.008
9	0.984	1.702	2.141	2.977	3.924
10	0.964	1.671	2.103	2.927	3.858
11	0.947	1.646	2.073	2.885	3.804
12	0.933	1.624	2.048	2.851	3.760
13	0.919	1.606	2.026	2.822	3.722
14	0.909	1.591	2.007	2.796	3.690
15	0.899	1.577	1.991	2.776	3.661
16	0.891	1.566	1.977	2.756	3.637
17	0.883	1.554	1.964	2.739	3.615
18	0.876	1.544	1.951	2.723	3.595
19	0.870	1.536	1.942	2.710	3.577
20	0.865	1.528	1.933	2.697	3.561
21	0.859	1.520	1.923	2.686	3.545
22	0.854	1.514	1.916	2.675	3.532
23	0.849	1.508	1.907	2.665	3.520
24	0.845	1.502	1.901	2.656	3.509
25	0.842	1.496	1.895	2.647	3.497
30	0.825	1.475	1.869	2.613	3.454
35	0.812	1.458	1.849	2.588	3.421
40	0.803	1.445	1.834	2.568	3.395

TABLE IXB. One-sided tolerance limits, K_{TL}.

C = 0.9

P

n	0.9	0.95	0.99	0.999	0.9999
3	4.259	5.311	7.340	9.651	11.566
4	3.188	3.957	5.438	7.129	8.533
5	2.742	3.400	4.666	6.111	7.311
6	2.493	3.091	4.243	5.555	6.645
7	2.332	2.894	3.972	5.202	6.222
8	2.218	2.755	3.783	4.955	5.927
9	2.133	2.649	3.641	4.771	5.708
10	2.065	2.568	3.532	4.628	5.538
11	2.011	2.503	3.443	4.514	5.402
12	1.966	2.448	3.371	4.420	5.290
13	1.928	2.403	3.309	4.341	5.196
14	1.895	2.363	3.257	4.273	5.116
15	1.867	2.329	3.212	4.215	5.046
16	1.842	2.299	3.172	4.164	4.986
17	1.819	2.272	3.137	4.119	4.932
18	1.800	2.249	3.105	4.078	4.884
19	1.781	2.228	3.077	4.042	4.841
20	1.765	2.208	3.052	4.009	4.802
21	1.750	2.190	3.028	3.979	4.766
22	1.736	2.174	3.006	3.952	4.734
23	1.724	2.159	2.987	3.926	4.704
24	1.712	2.145	2.969	3.903	4.677
25	1.701	2.132	2.952	3.882	4.651
30	1.657	2.080	2.884	3.794	4.546
35	1.623	2.041	2.883	3.729	4.470
40	1.598	2.010	2.793	3.678	4.411
45	1.576	1.986	2.761	3.638	4.363
70	1.772	2.153	2.974	3.906	4.677

TABLE IXC. One-sided tolerance limits, K_{TL}.

C = 0.95

n	0.9	0.95	0.99	0.999	0.9999
3	6.157	7.655	10.553	13.857	16.597
4	4.162	5.145	7.042	9.214	11.019
5	3.406	4.202	5.741	7.502	8.966
6	3.006	3.707	5.062	6.611	7.900
7	2.755	3.399	4.642	6.063	7.244
8	2.582	3.188	4.353	5.687	6.796
9	2.454	3.031	4.143	5.413	6.469
10	2.354	2.911	3.981	5.203	6.218
11	2.275	2.815	3.852	5.036	6.020
12	2.210	2.736	3.747	4.900	5.858
13	2.155	2.670	3.659	4.787	5.723
14	2.109	2.614	3.584	4.690	5.608
15	2.068	2.566	3.520	4.607	5.509
16	2.032	2.523	3.463	4.535	5.423
17	2.001	2.486	3.414	4.571	5.348
18	1.974	2.453	3.370	4.415	5.281
19	1.949	2.423	3.331	4.363	5.221
20	1.925	2.396	3.295	4.318	5.167
21	1.905	2.372	3.263	4.277	5.117
22	1.886	2.349	3.233	4.239	5.073
23	1.869	2.329	3.206	4.204	5.031
24	2.153	2.662	3.640	4.755	5.681
25	2.129	2.633	3.601	4.706	5.623
30	2.030	2.516	3.447	4.508	5.389
35	1.957	2.430	3.334	4.364	5.219
40	1.902	2.364	3.249	4.255	5.090
45	1.857	2.312	3.180	4.168	4.987
50	1.821	2.269	3.125	4.097	4.903
60	1.764	2.203	3.038	3.987	4.774
70	1.772	2.153	2.974	3.906	4.677

TABLE IXD. One-sided tolerance limits, K_{TL}.

C = 0.99

P

n	0.9	0.95	0.99	0.999	0.9999
3	13.998	17.372	23.896	31.348	37.532
4	7.379	9.084	12.387	16.175	19.327
5	5.362	6.579	8.939	11.649	13.906
6	4.411	5.406	7.335	9.550	11.395
7	3.859	4.728	6.412	8.346	9.957
8	3.497	4.286	5.812	7.564	9.024
9	3.240	3.973	5.389	7.014	8.368
10	3.048	3.739	5.074	6.605	7.881
11	2.898	3.556	4.829	6.288	7.503
12	2.777	3.410	4.633	6.035	7.201
13	2.677	3.290	4.472	5.827	6.954
14	2.593	3.189	4.337	5.652	6.747
15	2.521	3.103	4.222	5.504	6.571
16	2.459	3.028	4.123	5.377	6.419
17	2.405	2.963	4.037	5.265	6.287
18	2.357	2.905	3.960	5.167	6.170
19	2.314	2.854	3.892	5.079	6.066
20	2.276	2.808	3.832	5.001	5.974
21	2.241	2.767	3.777	4.931	5.890
22	2.209	2.729	3.727	4.867	5.814
23	2.180	2.694	3.681	4.808	5.745
24	2.153	2.662	3.640	4.755	5.681
25	2.129	2.633	3.601	4.706	5.623
30	2.030	2.516	3.447	4.508	5.389
35	1.957	2.430	3.334	4.364	5.219
40	1.902	2.364	3.249	4.255	5.090
45	1.857	2.312	3.180	4.168	4.987
50	1.821	2.269	3.125	4.097	4.903
60	1.764	2.203	3.038	3.987	4.774

TABLE IXE. One-sided tolerance limits, K_{TL}.

C = 0.999

P

n	0.9	0.95	0.99	0.999	0.9999
3	44.429	55.111	75.775	99.385	118.979
4	16.120	19.814	26.978	35.203	42.047
5	9.781	11.970	11.223	21.114	25.190
6	7.246	8.849	11.964	15.549	18.539
7	5.920	7.223	9.754	12.668	15.098
8	5.112	6.234	8.415	10.924	13.018
9	4.569	5.573	7.521	9.763	11.633
10	4.180	5.098	6,881	8.932	10.643
11	3.886	4.741	6.401	8.309	9.902
12	3.655	4.462	6.026	7.824	9.324
13	3.470	4.238	5.726	7.436	8.861
14	3.317	4.053	5.478	7.116	8.481
15	3.189	3.899	5.272	6.849	8.164
16	3.080	3.767	5.096	6.622	7.894
17	2.985	3.653	4.944	6.427	7.662
18	2.037	3.554	4.813	6.257	7.460
19	2.830	3.466	4.969	6.107	7.282
20	2.765	3.388	4.592	5.974	7.124
21	2.706	3.319	4.500	5.855	6.982
22	2.654	3.256	4.417	5.748	6.856
23	2.606	3.199	4.341	5.651	6.741
24	2.563	3.147	4.272	5.562	6.636
25	2.523	3.099	4.210	5.482	6.540
30	2.364	2.910	3.960	5.162	6.161
35	2.251	2.775	3.783	4.935	5.893
40	2.165	2.673	3.649	4.764	5.691
45	2.097	2.593	3.545	4.630	5.532
50	2.042	2.528	3.460	4.522	5.405
60	1.574	2.428	3.330	4.357	5.209

50.3.4.2 Correcting the sample size in variable sampling plans. It may seem that the sample size is determined by simply counting the number of devices tested. However, to show that this is not necessarily the case, consider the following hypothetical situation. Suppose a manufacturer ships a lot consisting of a large number of devices but the lot is made up of only a few wafer lots. Also, suppose that the devices from a given wafer lot are very uniform as compared to the difference which exist between different wafer lots. For illustration purposes, suppose that 5 wafer lots entered into a shipment in approximately equal proportions, and the average parameter x_{avg} varied from wafer lot to wafer lot according to a normal distribution. A measurement on a large number of devices would give the probability distribution on figure 14. Even if thousands of individual devices were used in a measurement, since the major cause of variation amongst the devices was the wafer-lot variations, and only 5 wafer lots were sampled, the true sample size is only 5. In such a case, calculations for one-sided tolerance limits and so forth should use the value 5 for the sample size.

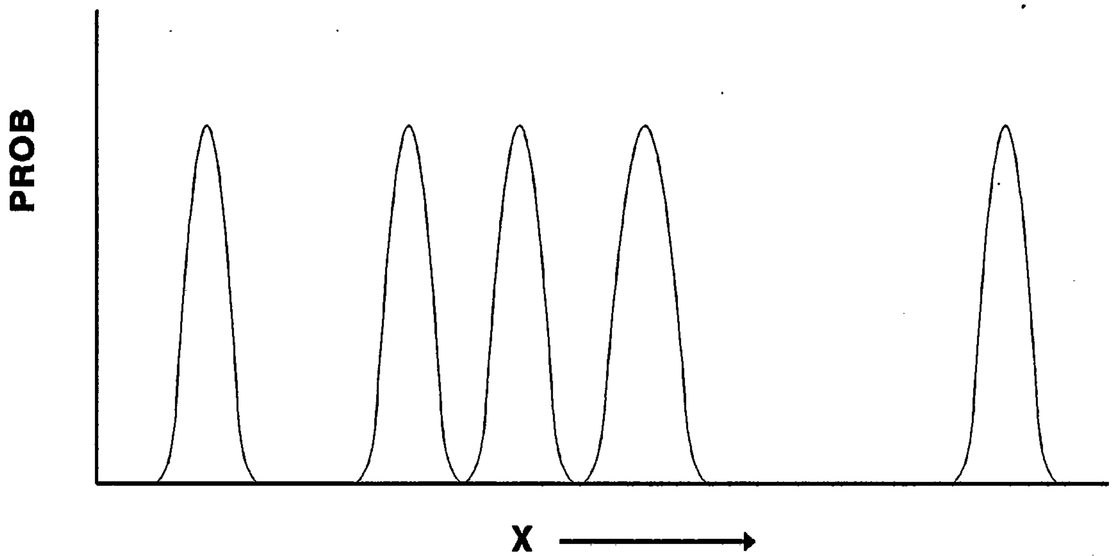

FIGURE 14. Hypothetical shipment with 5 wafer lots.

50.3.4.2.1 Complications. A more typical problem would be much more complicated than the illustrated one because the number of wafer lots in the shipment would not be known, they may not enter into the shipment in equal proportions, the variations between wafer lots may not always be large compared to the variations within a particular wafer lot and for many other reasons. Furthermore, a typical characterization test would include several manufacturers, so that, manufacturer to manufacturer variations would also come into play.

50.3.4.2.2 Checking. Clearly, for any measurement there is an effective sample size which will always be equal to or less than the actual number of devices measured. The determination of this size is a somewhat complex procedure involving chi-squared tests described in reference 60.16. Such tests should be standard procedure, especially for characterization measurements, to check the fit of the data to the assumed probability distribution.

50.4 Calculation of survival probabilities. The ultimate goal of a probability analysis is to calculate the survival probability of a system. This is typically expressed as

$$P_{survival} = p^n$$

where p^n is the individual part survival probability multiplied together n-times where n is the total number of parts.

50.4.1 One approach. A common practice for obtaining a more conservative estimate that a system composed of n parts from a lot will survive is

$$P_{survival} = Cp^n$$

where with confidence, C, at least proportion, P of the lot is estimated to survive. This estimate is generally very conservative because (a) P is a minimum estimate that the part will survive with confidence, C and (b) it may not be necessary for all the parts to survive. For example, there may be redundancies in the system allowing undamaged parts to take over the functions of damaged ones. A precise analysis of the system would require the services of a statistician and an expert familiar with the details of the specific system.

50.4.2 Monte Carlo simulations. In extremely complicated situations where a fairly precise estimate must be made for the survivability of a circuit or a system it may be necessary to perform a Monte Carlo simulation of the system behavior on a computer. A good fundamental introduction to such simulations is given in 60.16. Monte Carlo analyses are frequently used in problems such as shielding calculations and neutron transport calculations (see, for example, 60.17). The basic idea is to simulate parameters which vary according to the same law. In practice, the methods for arriving at a reasonably precise answer without consuming too much computer time are quite sophisticated and expert advice would be essential. The reader should be aware of what such techniques have to offer. Their advantages are:

a. In highly complex situations where a good estimate of survival is necessary, this is often the only way to obtain a realistic answer.

b. The method is very versatile and applicable to a wide range of problems.

The disadvantages are:

a. The calculations are generally very costly in terms of the effort required (the order of half a man-year) and in terms of computer costs ($10,000 would not be unreasonable for a difficult problem).

b. Such a calculation would still be subject to all the errors inherent in imprecise modeling of the system and the use of probability distributions which do not precisely reflect reality.

50.5 Approximate values of K_{TL} for P > 0.9999. If 60.15 is not easily available, values of K_{TL} for P > 0.9999 will be difficult to find. It may be useful here, therefore, to present a method, not previously published, for obtaining approximate values of K_{TL}. The method uses the values given in tables X and XI and the formulas at the ends of the tables. The method can also be used to obtain values of K_{TL} for values of P which are not included in table IX. Table X also includes estimated errors for this quantity. The values in tables X and XI may be used to calculate values of K_{TL} for values of P down to 0.9 with errors as great as 15 percent for n > 5 as shown on the tables.

50.5.1 Tolerance limits calculations. For application of the factors given in table X, values of K_{TL} are such that with confidence C at least proportion P of a normal distribution is less than

$$m + K_{TL}s$$

where m and s are the measured mean and standard deviation respectively and may be approximated by

$$K_{TL} \sim A\overline{F}_n(P) + \frac{B}{\overline{F}_n(P)}$$

where the function, $\overline{F}n(P)$ is such that exactly the proportion, P, of a normal distribution is less than

$$m + \overline{F}n(P)\,s$$

The values of A and B are listed in tables XA through XC, columns 2 and 3 respectively as functions of C and n. A few values of $F_n(P)$ are given in table XI.

TABLE XA. Values for calculating approximate one-sided tolerance limits.

C = 0.9

n	A	B
3	3.0808	0.4503
4	2.2658	0.4190
5	1.9393	0.3875
6	1.7621	0.3604
7	1.6499	0.3376
8	1.5719	0.3183
9	1.5141	0.3018
10	1.4694	0.2875
11	1.4337	0.2750
12	1.4043	0.2639
13	1.3797	0.2540
14	1.3587	0.2452
15	1.3406	0.2371
16	1.3248	0.2298
17	1.3108	0.2232
18	1.2983	0.2170
19	1.2871	0.2113
20	1.2770	0.2061
21	1.2678	0.2012
22	1.2594	0.1966
23	1.2517	0.1924
24	1.2446	0.1883
25	1.2380	0.1846
30	1.2112	0.1686
35	1.1914	0.1561
40	1.1761	0.1460

Estimated maximum errors in computing part categorization criteria for n > 5 using this table

	Percent error
$P \geq 0.999$	0.6
$P \geq 0.9$	2

TABLE XB. Values for calculating approximate one-sided tolerance limits.

C = 0.95

n	A	B
3	4.4154	0.5157
4	2.9200	0.4932
5	2.3724	0.4628
6	2.0893	0.4345
7	1.9154	0.4096
8	1.7971	0.3881
9	1.7110	0.3694
10	1.6452	0.3530
11	1.5931	0.3384
12	1.5506	0.3255
13	1.5153	0.3139
14	1.4854	0.3034
15	1.4597	0.2939
16	1.4373	0.2852
17	1.4176	0.2773
18	1.4001	0.2699
19	1.3845	0.2631
20	1.3704	0.2568
21	1.3576	0.2509
22	1.3460	0.2454
23	1.3353	0.2402
24	1.3255	0.2353
25	1.3165	0.2308
30	1.2797	0.2113
35	1.2528	0.1960
40	1.2320	0.1836

Estimated maximum errors in computing part categorization criteria for $n > 5$ using this table

	Percent error
$P \geq 0.9999$	1
$P \geq 0.9$	2.5

TABLE XC. Values for calculating approximate one-sided tolerance limits.

C = 0.99

n	A	B
3	9.9749	0.5998
4	5.1112	0.5933
5	3.6692	0.5820
6	3.0034	0.5559
7	2.6230	0.5304
8	2.3769	0.5069
9	2.2043	0.4856
10	2.0762	0.4665
11	1.9771	0.4493
12	1.8980	0.4337
13	1.8333	0.4196
14	1.7792	0.4067
15	1.7332	0.3948
16	1.6936	0.3840
17	1.6592	0.3740
18	1.6288	0.3646
19	1.6019	0.3560
20	1.5777	0.3479
21	1.5560	0.3403
22	1.5363	0.3332
23	1.5184	0.3266
24	1.5019	0.3203
25	1.4868	0.3143
30	1.4262	0.2889
35	1.3825	0.2688
40	1.3491	0.2523

Estimated maximum errors in computing part categorization criteria for $n > 5$ using this table

Percent error

	$n \geq 5$	$n \geq 10$
$P \geq 0.9999$	5	2
$P \geq 0.9$	12	4

TABLE XI. The anti-function of the standard normal distribution.

$F_n(P)$ is such that for a normal distribution with mean, μ, and standard deviation, σ, proportion P of the distribution is less than (see figure 15.)

$$\mu + \bar{F}_n(P)\sigma$$

P	0.9	0.95	0.99	0.999	0.9999	0.99999	0.999999
$\bar{F}_n(P)$	1.282	1.645	2.326	3.090	3.719	4.265	4.753

P	0.1	0.05	0.01	0.001	0.0001	10^{-5}	10^{-6}
$\bar{F}_n(P)$	-1.282	-1.645	-2.326	-3.090	-3.719	-4.265	-4.753

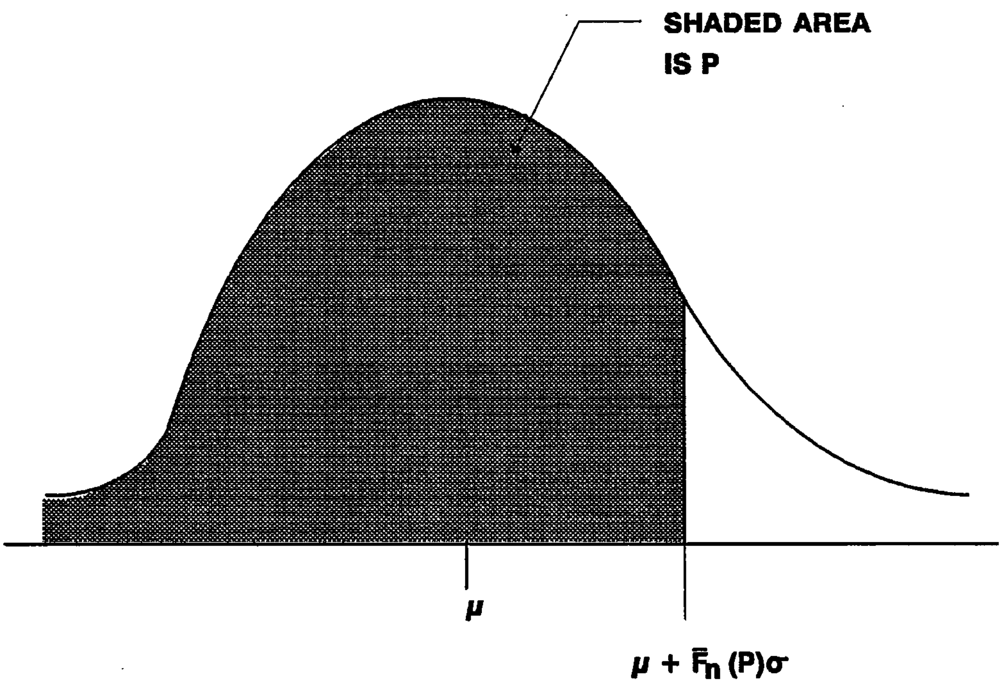

FIGURE 15. Anti-function of a normal distribution.

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CONCLUDING MATERIAL

Custodians:
Army - ER
Navy - EC
Air Force - 19
NASA - NA

Review activities:
Army - AR, MI, PA
Navy - MC, TD
Air Force - 17, 85, 99
DLA - ES

Preparing Activity:
Navy - EC

Agent:
DLA - ES

(Project 59GP-0128)