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MIL-HDBK-816
NOTICE 1
8 April 2002

DEPARTMENT OF DEFENSE
HANDBOOK

GUIDELINES FOR DEVELOPING RADIATION HARDNESS ASSURANCE DEVICE SPECIFICATIONS

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PREFACE

This document discusses how data on the performance of an electronic part should be taken and documented so that it can be easily analyzed and how end-point limits for pass-fail lot acceptance tests should be calculated. Although these guidelines specifically address problems of radiation hardness assurance, many of the discussions given may be useful more generally to persons responsible for electrical response measurements and/or the development of procurement specifications.

ACKNOWLEDGEMENTS

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TABLES PAGE

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1. SCOPE

1.1 Scope. The primary objective of this document is to provide guidelines and easy to follow procedures for the preparation of detailed device specifications for the procurement of microcircuits and semiconductor devices where radiation Hardness Assurance (RHA) is required. The guidelines are applicable to MIL-M-38510, MIL-PRF-38534, MIL-PRF-38535, and MIL-PRF-19500 microcircuit and semiconductor device detailed specifications, Standard Microcircuit Drawings (SMDs) as well as other contractor prepared specifications such as Source Control Drawings (SOCD), Selected Item Drawings (SID), and Specification Control Drawings (SCD). Recommended procedures are provided for characterizing the radiation response of a part and for obtaining post-irradiation post-irradiation end-point limits for qualification and Lot Acceptance Tests (LAT).

1.2 Radiation hardness assurance at the piece part level. These guidelines address radiation response measurement and hardness assurance questions at the piece part level. In keeping with the present scheme for military standard RHA device specifications, which only addresses ionizing radiation dose effects measured at 50 to 300 rads(Si)/second (see table I), these guidelines emphasize that radiation environment. However, because the addition of dose rate and Single Event Upset (SEU) specifications is now under consideration, brief mention of these two radiation events is also included. The principles discussed are applicable to both bipolar and MOS silicon transistors and integrated circuits, and to devices made from gallium arsenide and other semiconductor materials. They have, furthermore, been presented in terms of the intrinsic performance characteristics of the part independent of any system in which it may be used. For military standard specifications, the levels shown in table I are used as reference points. The general principles may be applied to system specific requirements.

1.3 LAT end-point limits. The procedure for measuring radiation response characteristics and for calculating LAT end-point limits are discussed in terms of parts whose design and production processes are mature and stable. That is, these guidelines do not attempt to discuss the case where the part is still under development or is not under change control, and hence its characteristics are subject to change. It is recognized that this latter case is important and occurs frequently because system designers are interested in obtaining the most advanced parts for their systems. The process of obtaining LAT end-point limits for such parts, however, involves testing and iterative end-point adjustments by the part manufacturer and the system parts engineers and designers which would be difficult to formulate as a set of generalized steps which could be applied to a variety of system needs. Because military standard procurements of RHA devices use attribute sample size series LAT tests (see Appendix D of MIL-PRF-38535), the end-point limit discussions here emphasize sample size series tests.

1.4 Low yield devices. If sample costs are affordable, the LAT methods discussed will be performed on samples of the devices themselves. In the case of Very Large Scale Integration (VLSI) devices, one possible option might be to use devices for LAT which are acceptable from an electrical performance standpoint but do not meet all the normal visual acceptance criteria. Such devices are said to be selected according to “alternate” visual criteria. Another possible option might be to use test structures for LAT which have been processed on the same wafers as the lot under consideration. By test structures are meant simpler and less expensive microcircuits which have been designed specifically to correlate with the radiation response characteristics and failure levels of the subject VLSI circuit; radiation tests on the test structure can then be used to estimate the performance characteristics of the VLSI circuit. The use of test structures for LAT cannot be recommended until data and experience show definitively that test structure responses correlate reliably with the actual devices.

1.5 Qualified manufacturers list program. The qualified manufacturers list (QML) program allows a device manufacturer the flexibility to implement best commercial practices to the maximum extent possible, while still providing product that meets the military performance needs and whose performance is stable. The manufacturing line is controlled through the manufacturer’s quality management (QM) program once the QM program has been certified and qualified. Several levels of product assurance, including radiation hardness assurance (RHA), are provided for. For those devices that will be certified as RHA, the manufacturer must have a technology review board that is cognizant of the factors that affect radiation hardness assurance. In addition, the manufacturer needs an RHA QM plan that establishes the procedures to be followed to ensure that the devices meet the radiation hardness assured capability level that the manufacturer has selected. The certification requirements for an RHA product include a process capability demonstration, wafer fabrication certification, and a wafer acceptance plan. This topic is discussed in much more detail in MIL-PRF-19500, MIL-PRF-38534, and MIL-PRF-38535.

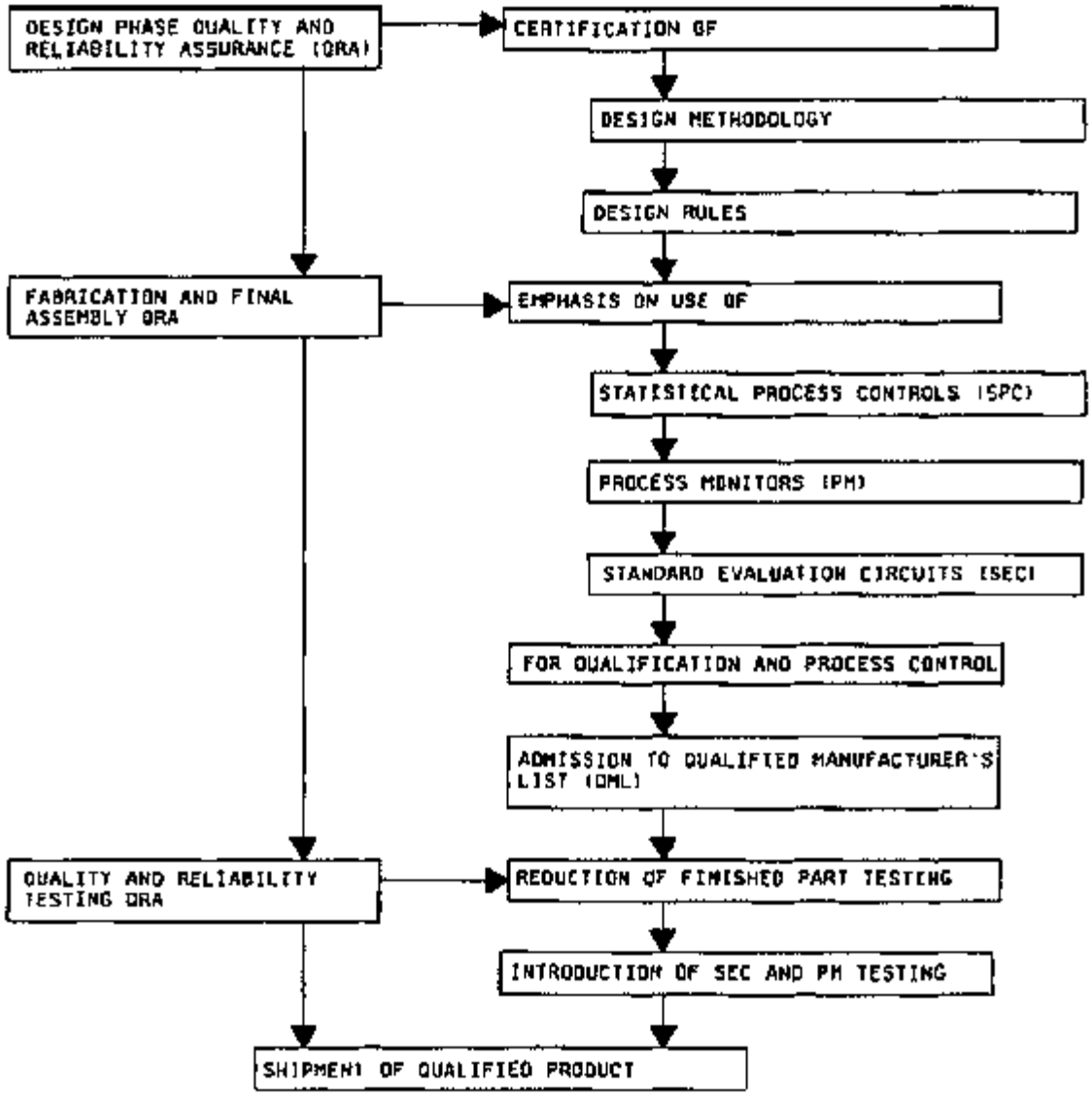

FIGURE 1. Proposed generic qualification system.

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2. APPLICABLE DOCUMENTS

2.1 General. The documents listed below are not necessarily all of the documents referenced herein, but are the ones that are needed in order to fully understand the information provided by this handbook.

2.2 Government documents.

2.2.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the latest issue of the Department of Defense Index of Specifications and Standards (DoDISS) and supplement thereto.

SPECIFICATIONS

DEPARTMENT OF DEFENSE

DNA-TR-84-220-V1	-	Hardness Assured Device Specifications for Moderate Requirements.
DNA-TR-84-220-V2	-	Hardness Assured Device Specification a 4K X 1 CMOS/SOS Static RAM.
DNA-TR-81-90	-	Hardness Assured Device Specifications.
MIL-M-38510	-	Microcircuits, General Specification for.
MIL-PRF-19500	-	Semiconductor Devices, General Specification for.
MIL-PRF-38534	-	Hybrid Microcircuits, General Specification for.
MIL-PRF-38535	-	Integrated Circuits (Microcircuits) Manufacturing, General Specification for.

STANDARDS

DEPARTMENT OF DEFENSE

MIL-STD-750	-	Test Method Standard for Semiconductor Devices.
MIL-STD-883	-	Test Method Standard, Microcircuits.

HANDBOOKS

DEPARTMENT OF DEFENSE

MIL-HDBK-103	-	List of Standard Microcircuit Drawings.
MIL-HDBK-339	-	Custom Large Scale Integrated Circuit Development and Acquisition for Space Vehicles.
MIL-HDBK-814	-	Ionizing Dose and Neutron Hardness Assurance Guidelines for Microcircuits and Semiconductor Devices.
MIL-HDBK-815	-	Dose-Rate Hardness Assurance Guidelines
MIL-HDBK-817	-	System Development Radiation Hardness Assurance

(Unless otherwise indicated, copies of the specifications, standards, and handbooks are available from the Document Automation and Production Services (DAPS), Building 4D (DPM-DODSSP), 700 Robbins Avenue, Philadelphia, PA 19111-5094.)

2.2.2 Other Government documents, drawings, and publications. The following other Government documents, drawings, and publications form a part of this document to the extent specified herein.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

SCR-607 - Factors for One-Sided Tolerance Limits and for Variables Sampling Plans.

(Copies are available from the National Aeronautics and Space Administration (NASA), Ames Research center, Mail Stop 213-4, Moffett Field, CA 94035.)

NATIONAL TECHNICAL INFORMATION SERVICE (NTIS)

Experimental Statistics Handbook

(Copies are available from the U.S. Department of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.)

2.3 Non-Government publications. The following documents form part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the latest issue of the DoDISS, and supplement thereto.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

Annual Book of ASTM Standards International, Volume 12.02 - Nuclear, Solar, and Geothermal.
Annual Book of ASTM Standards International, Volume 10.04 and 10.05 - Electronics.

(Application for copies should be addressed to the American Society for Testing and Materials International (ASTM), 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.)

EIA/JEDEC STANDARDS

EIA/JEDEC-57 - Test Procedures for the Measurement of Single Event Effects in Semiconductor Devices from Heavy Ion Irradiation.
JESD-89 - Measurement and Reporting of Alpha Particles and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices.

(Application for copies should be addressed to Global Engineering Documents, 5 Inverness Way East, Englewood, CO 80112-5704.)

2.4 Order of precedence. In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. ACRONYMS, DEFINITIONS, AND SYMBOLS

3.1 Acronyms used in this handbook. The acronyms used in this handbook are defined as follows:

ASTM	-	American Society for Testing and Materials
DSCC	-	Defense Supply Center, Columbus
DNA	-	Defense Nuclear Agency (now DTRA)
DOD	-	Department of Defense
DTRA	-	Defense Threat Reduction Agency
DTRIAC	-	Defense Threat Reduction Information Analysis Center
EPL	-	End Point Limits
ERRIC	-	Electronics Radiation Response Information Center
ESD	-	Electrostatic Discharge
GQ	-	General Qualification

HA	-	Hardness Assurance
JAN	-	Joint Army Navy (military specification trademark)
LAT	-	Lot Acceptance Tests
LET	-	Linear Energy Transfer (produced when a high energy ionizing particle traverses a solid)
MIL-HDBK	-	Military Handbook
MIL-PRF	-	Military Performance Specification
MIL-STD	-	Military Standard
MOS	-	Metal Oxide Semiconductor
NASA	-	National Aeronautics and Space Administration
SPAWAR	-	Space and Naval Warfare Systems Command
PIPL	-	Post-Irradiation Parameter Limit (the same as RHEPL in this document)
PM	-	Process Monitor
PRF	-	Pulse Repetition Frequency
QA	-	Quality Assurance
QCI	-	Quality Conformance Inspection
QM	-	Quality Management
QML	-	Qualified Manufacturer's List
QPL	-	Qualified Parts List
QRA	-	Quality and Reliability Assurance
RHA	-	Radiation Hardness Assured or Radiation Hardness Assurance
RHEPL	-	Radiation Hardness Assurance End-Point Limit
SCD	-	Specification Control Drawing
SEC	-	Standard Evaluation Circuit
SEE	-	Single Event Effects
SEP	-	Single Event Phenomena
SEU	-	Single Event Upset
SID	-	Selected Item Drawing
SMD	-	Standard Microcircuit Drawing
SOCD	-	Source Control Drawing
SPC	-	Statistical Process Control
STD	-	Standard
TCI	-	Technology Conformance Inspections
TCV	-	Technology Characterization Vehicle
ULSI	-	Ultra Large Scale Integration
VLSI	-	Very Large Scale Integration

3.2 General usage for definitions and symbols. To make this handbook easier to read for those who will need to refer to it only infrequently, an attempt has been made to devise a mathematical notation which is more self-explanatory than the notations used in other recent reports related to hardness assurance. This notation is used in the definitions listed in this section and throughout the rest of the handbook. As an example of the differences, the present notation uses MEAN(PAR) and GMEAN(PAR) for the measured arithmetic and geometric mean values, respectively, of a parameter; in several other reports an overline on the word PAR is used to indicate the arithmetic mean value and PAR_M is used to denote the geometric mean value. Conversions to the other notations, if necessary, should present no difficulties. The following is a list of specific definitions:

Absorbed dose	-	The absorbed energy usually expressed in rads.
c(lower case)	-	The acceptance number in a sample size series test.
Confidence level	-	The chance of rejecting a lot where there is less than probability P that any part from the lot can pass the test condition.
Device specification	-	The contractual document to which an electronic device is either sold or purchased.
Diffusion lot	-	A set of wafers heated at one time in one diffusion furnace.
Dose	-	See Ionizing Radiation Dose.
Dose Rate	-	Rads per second due to ionizing radiation.
Exp(x)	-	Napier's constant, e, to the x-th power. Please note that an exponent can only be a pure number. Therefore, if the notation shows a variable that has a dimension (such as an ionizing radiation dose expressed in rads, for example) as an exponent, it should be understood that the exponent has been made dimensionless by dividing it by a quantity having a value of one but with the same dimensions as the variable in question.
Fluence	-	The accumulated number of irradiating particles per square centimeter.
Goodness of fit	-	The degree to which a measured probability distribution fits the assumed distribution; the CHI-square test is commonly used to determine the goodness of fit.
Gray	-	10,000 ergs of absorbed energy per gram; equals 100 rads.
i(lower case)	-	The subscript used to label the i-th device in a sample of devices.
I(upper case)	-	The subscript used to label the I-th lot in a sample of lots.
In-flux	-	Measurements made on a device while it is being irradiated.
Ionizing radiation dose	-	The accumulated absorbed energy in rads or Grays due to ionizing radiation.
JAN parts	-	JAN parts are listed in the Qualified Manufacturers List (QML) and undergo scheduled periodic audits by the qualifying activity to MIL-M-38510, MIL-PRF-19500, MIL-PRF-38534, and MIL-PRF-38535 requirements.
$TL^{(n, C,P)}$	-	One-sided tolerance limit. This factor takes into account the certainties resulting from small sample size statistics. It is applied to normal distributions as follows: For a sample size n, if MEAN(PAR) and STDEV(PAR) are the measured mean and standard deviation respectively for parameter PAR, then with confidence C, there is probability P, that future measurements of the parameter PAR will be less than:

$$\text{MEAN(PAR)} + K_{TL}(n, C, P) * \text{STDEV(PAR)}$$

Or larger than:

$$\text{MEAN(PAR)} - K_{TL}(n, C, P) * \text{STDEV(PAR)}$$

LN(X) - The natural logarithm of X. Please note that the argument of a logarithm can only be a pure number. Therefore, if the notation shows a logarithm of a variable that has a dimension (such as an ionizing radiation dose expressed in rads, for example), it should be understood that the argument has been made dimensionless by dividing it by a quantity having a value of one but with the same dimensions as the variable in question.

Lot - The population of parts from which a sample has been taken.

Lot acceptance test - The testing of a sample of parts from a lot to determine whether the lot is acceptable or not.

MEAN(X) - The arithmetic mean value of X.

$$\text{MEAN}(X) = 1/n \sum_{i=1}^{n} X_i$$

$$\text{e.g. MEAN [PAR (RAD)]} = 1/n \sum_{i=1}^{n} \text{PAR}_i(\text{RAD})$$

GMEAN(X) - The geometric (or logarithmic) mean value of X.

$$\text{e.g. MEAN [LN (PAR (RAD))]} = 1/n \sum_{i=1}^{n} \text{LN}(\text{PAR}_i(\text{RAD}))$$

$$\text{GMEAN}(X) = \text{EXP}(\text{MEAN}(\text{LN}(X)))$$

$$\text{e.g. GMEAN}(\text{PAR}(\text{RAD})) = \text{EXP}(\text{MEAN}(\text{LN}(\text{PAR}(\text{RAD}))))$$

n(lower case) - The number of devices in a sample of devices.

N(upper case) - The number of lots in a sample of lots.

Non-RHA devices - Parts that have not been tested with radiation or parts that fail the radiation test criteria.

Standard devices - Parts that meet the criteria for military specifications or for Standard Microcircuit Drawings (SMD).

Nonstandard devices - Parts that do not meet the criteria for military specifications or for Standard Microcircuit Drawings (SMD). There are three types of nonstandard parts that are used for military procurement. They are as follows: a) Selected Item Drawings (SID), b) Source Control Drawings (SOCD), and c) Specification Control Drawings (SCD).

Not-in-flux - Measurements made on a device when it is not being irradiated.

OSTL - One-sided tolerance limit.

P(upper case) - The probability that any part from a lot can pass the test conditions; also called the piece part survival probability.

PAR_i - The pre-rad parameter value measured for the i-th device.

$\text{PAR}_i(\text{RAD})$ - The post-rad parameter value measured for the i-th device.

Phi(spec) - The radiation level required in the device specification for lot acceptance tests.

RAD - Equals 100 ergs of absorbed energy per gram.

Radiation hardness assurance - The application of methods and procedures during the procurement of an electronic system to ensure that the radiation response of the system is within known and acceptable limits.

Radiation hardness maintenance - Procedures applied during the deployment phase to ensure that the system's operational procedures, maintenance requirements and aging characteristics maintain the system's hardness. These procedures include tests and inspections.

Radiation hardness surveillance - Periodic inspection and testing during the lifetime of deployed systems to ensure that, within acceptable tolerances, the radiation responses of the systems remain adequate for mission completion.

RHA devices - Parts labeled by letter designators which indicate that the part type has passed lot acceptance tests based on a sample of devices tested to the device specification radiation levels.

Selected item drawing - A specification that is written against any standard part when the system design has a critical requirement not covered by the standard part specification (QML or SMD). The acronym for this term is SID.

Standard microcircuit drawing - A specification written for parts which are listed in MIL-HDBK-103 and/or QML-38534 or QML-38535, and for which DSCC has a certificate of compliance to MIL-PRF-38534 or MIL-PRF-38535. Approved sources of supply are listed on this drawing. Periodic compliance verification audits are performed that data do not contain any faulty measurements or nonrandom effects. The data should be examined also for sufficiency. Data examination is all the more important when a significant amount of time has elapsed between the characterization measurements and the data analysis or when the person or organization undertaking the data analysis is different from the persons who took the data in the first place. Some of the most common reasons for suspecting that data may be bad are discussed below.

4. GENERAL CONSIDERATIONS

4.1 Device performance in the radiation environment. Many military and civilian electronic systems must operate reliably in radiation environments. The design of such systems therefore requires that the performance of the individual component semiconductor devices in radiation environments be characterized. The production of the systems then further requires that the parts purchased for production have characteristics at least as good as those on which the design was based. These guidelines discuss how to characterize the performance of semiconductor devices in radiation environments and how to obtain hardness assurance through device procurement specifications based on the characterization data. Applications to an existing system of military standard or QML detailed specifications for Radiation Hardness Assured (RHA) devices are emphasized but the discussions may be applied also to other part specifications. Radiation hardness assurance is generally achieved through the use of Lot Acceptance Test (LAT) in which parts from the lot being purchased are irradiated and tested. Because the military standard lot acceptance tests rely largely on pass-fail tests in which a part's performance is compared to a specified end-point limit, these guidelines discuss, specifically, how Radiation Hardness Assurance End-Point Limits (RHEPL) for such tests should be calculated from the characterization data.

4.1.1 Degrading effects of radiation. The performance of semiconductor devices can be degraded by exposure to radiation which produces ionization or displacement damage. Depending on the type of radiation incident on the device, the rate at which energy is absorbed, and the total accumulated amount of absorbed energy, the device performance can be degraded permanently or temporarily. Examples of temporary degradation are: (a) circuit upset due to the instantaneous photocurrent produced throughout the device by a short pulse of high intensity ionizing radiation or (b) circuit upset due to the collection of charge from a single, local, ionized particle track passing through the device. Upsets due to photocurrents are commonly called dose rate upsets; upsets due to the collection of charge from single ionized tracks are called Single Event Upsets (SEUs). Examples of permanent damage are: (a) device failures due to atomic displacements produced in the semiconductor (usually by neutrons), (b) failures due to trapped charge in insulating layers, which are present in most

devices, produced by ionizing radiation, or (c) latch-up or burnout produced by photocurrents or by single ionized tracks. Trapped charge effects are sometimes called ionizing radiation dose effects or total dose effects. However, because of time dependent effects after irradiation, specifying the total dose is not considered adequate for describing these effects.

4.1.2 Radiation hardness assurance. If nondestructive electrical measurements alone could be used to predict the performance of a part type in a radiation environment, then the hardness assurance problem would be largely solved. One of the cases where such measurements have proven useful has been that of using transistor current gain-bandwidth product, f_t, measurements to screen out (by requiring f_t to be above some minimum value) parts which would be extra sensitive to neutron displacement damage. For ionizing radiation dose, it is necessary to use actual radiation tests to assure the radiation response of a part. In practice, radiation hardness assurance is achieved most commonly through the use of LAT which are performed on the lots that are being purchased.

4.1.3 Dose rate tests. For the dose rate upsets discussed previously, if sufficient care is used, radiation tests can be non-damaging. Thus, parts which have been tested can be used for production. In this case 100 percent of the parts to be used for system production can be tested (screened) and a high degree of assurance can be obtained that the parts will meet system requirements. Caution is still required, because there exists some possibility, especially for complex microcircuits, that the screening tests conducted will not have covered the worst case conditions or exercised all possible paths. MIL-HDBK-815, entitled: “Dose-Rate Hardness Assurance Guidelines”, may be consulted for a detailed discussion of this problem.

4.1.4 Displacement damage, steady state ionization and single event upsets. For displacement damage, steady state ionization effects, and single event upsets, the radiation tests are damaging and it is generally not possible to use the tested parts in the system. The use of damaging radiation tests thus produces the central problem of hardness assurance, namely, that estimates of the survival probability of the parts to be used in the system must be based on statistical inference from a tested sample of parts which are degraded by the tests and therefore cannot be used in the system. This problem is compounded by the fact that production processes can vary so that the currently produced radiation hard parts may not be typical of those that were measured in the past. This case, which is common, has been carefully reviewed by both users and manufacturers of semiconductor devices. The consensus opinion is that, if no additional information is available, the degree of hardness assurance obtained from the detailed specification is limited statistically to that provided by the radiation LAT or Quality Conformance Inspection (QCI) that are performed (the term QCI is reserved for tests performed by the manufacturer before the lot is approved for shipment).

4.2 Military Standard procurement system. In order to make high reliability hardness assured devices available to designers and manufacturers of systems, the existing military standard procurement system was augmented a few years ago to include RHA semiconductor devices. At the present time, QML RHA parts are labeled by letter designators which indicate that the part type has passed lot acceptance tests based on a sample of parts tested at the radiation levels shown in table I.

4.3 Lot acceptance tests. Lot acceptance tests are used in the military standard system for determining whether a production lot is of high enough quality so that it can be shipped by the vendor. The tests are of a statistical nature and fall into two general categories: (a) attribute tests and (b) variables tests.

4.3.1 Attribute variables tests. Attribute tests are the tests most often used in the military standard procurement system. For this reason, these guidelines will be directed at the use attribute tests for lot acceptance. Variables tests, on the other hand, are often used for qualifying and accepting system production parts and, for such use, may depend on the particular hardness assurance and derating procedures that the given system is using. Variables tests, therefore, more properly should be discussed as part of a system hardness assurance guideline document and, for that reason, are not discussed in detail here.

TABLE I. Military standard RHA detailed specifications.

Hardness assurance levels		
Letter designator *	Ionization effects **	Neutrons ***
/	No RHA	No RHA
M	3×10^3 rad(SI)	2×10^{12}
D	1×10^4 rad(SI)	2×10^{12}
P	3×10^4 rad(SI)	2×10^{12}
L	5×10^4 rad(SI)	2×10^{12}
R	1×10^5 rad(SI)	2×10^{12}
F	3×10^5 rad(SI)	2×10^{12}
G	5×10^5 rad(SI)	2×10^{12}
H	1×10^6 rad(SI)	2×10^{12}

* For microcircuits, the letter designator for RHA parts replaces the slash in the part number; e.g., 38510R291A in place of 38510/291A. For discrete devices it is a suffix, e.g., JANTXVR.
** At a dose rate of 200 rads(SI)/sec plus or minus 100 rads(SI)/sec.
*** 1 MeV silicon displacement damage equivalent neutron fluence. Test to be conducted only when specified in the purchase order or contract.

4.3.1.1 Advantages and disadvantages of attribute tests. An advantage of the attribute tests is that the data collection and analysis are simple and relatively inexpensive. A further important advantage is that the test is distribution free (i.e., no assumptions are required about probability distributions). However, a major drawback is that the tests require inordinately large sample sizes if significant survival probability requirements are imposed. For example, to check with 90 percent confidence that a lot has at least 99 percent survivable parts, i.e., that the sample size series number is 1 percent or less, it is necessary to test a sample of at least 231 parts with no failures. It is interesting to note that attribute tests can be applied to attributes that can assume more than just the two values of pass or fail. Acceptance criteria for lots can also be based on a mix of attributes that may be desired (e.g., with confidence C the probability of a given attribute must be between 49.9 percent and 50.1 percent).

4.3.1.2 The n/c test. The most common type of attribute test is the so called n/c test where a sample of n parts is tested and if more than c of the parts fail the test then the lot is rejected. The significant test result for each part is the attribute of passing or failing and hence the term attribute test. The usual failure criteria for the parts are: (a) functional failure or (b) deterioration of any critical parameter past an acceptable limit.

4.3.1.3 Multiple sampling. Some attribute tests allow the drawing of extra samples if lots fail on the first try (multiple sampling plans). A common multiple sampling plan used in the military standard system, for example, is a test of 11 parts where the lot is passed if there are no failures. Then, if there is exactly one failure, an additional seven parts may be sampled and tested with no further failures allowed. If there is a total of two or more failures, the original lot is rejected.

4.3.2 Confidence and probability. The results of the military standard attribute lot acceptance test are phrased in terms of a confidence C which is the chance of rejecting a lot where there is less than a probability P that any part in the lot can pass the test conditions.

4.3.2.1 Usual confidence and probability. In the military standard system, the significance of an n/c attribute test is usually given in terms of 90 percent confidence and a quantity called the Sample Size Series Tests which may be found, for example, in MIL-PRF-38535, Appendix D, the general specification for microcircuits. Thus, for example, the sample size series associated with an 11/0 sample size/accept number test may be found in the table to be 20 percent. An 11/0 sample size/accept number test will therefore provide 90 percent confidence that a lot with 20 percent defective parts or greater will be rejected. In terms of the probability P mentioned in 4.3.2, the sample size series number equals 1 minus P.

4.3.3 Variables tests. Variables LAT tests measure a post-irradiation parameter and apply statistical analysis using approximate or exact probability distributions to describe the variability of that parameter (hence the term variables). Usually pre-irradiation values are also measured and they often figure in the analysis (e.g., when the quantity of interest is the change in the parameter, sometimes referred to also as the parameter “delta”). Sometimes the variable of concern is the stress to failure.

4.3.3.1 Advantages and disadvantages of variables tests. The major advantage of variables tests is that a high probability requirement may be imposed even if the sample size is only moderate (typically 10-50 parts). A disadvantage is that the measurements and analysis are generally more complex and expensive. The major disadvantage, however, is that assumptions must be made about the probability distribution governing the failure of parts. If the distribution is very well known, then this technique can yield high probabilities with high confidences. However, it is usually difficult to know the “wings” of the distribution accurately. Therefore, extrapolations to excessively high probabilities (such as 0.999) based on experience with only a few parts must be regarded with skepticism. It is important to note that, for some kinds of electronics effects (e.g., latch-up), there is very little reliable information about the nature of the governing probability distribution.

4.3.3.2 Variables tests depend on tolerance limits. Variables tests depend on tolerance limits which must be compared with the given specifications for the parameter or stress. A lot is rejected if the parameter in question deteriorates beyond an acceptable limit (or if the stress to failure is below the required specification). The tolerance limits are chosen such that with confidence C, the probability is at least P that parts will not fail the test.

4.3.3.3 Confidence and probability for variables tests. There is a confidence C of rejecting a lot if there is less than probability P that any part in the lot will meet the specified parameter (or stress) tolerance limit.

4.3.3.4 Lognormal distribution. The most commonly assumed distribution for the testing of electronic parts is the lognormal distribution (in the lognormal distribution it is the logarithm of the quantity that is normally distributed). The normal distribution is also frequently used. Other probability distributions which have been suggested for some circumstances are the Weibull distribution and the extreme value distribution. If enough parts have been tested, the characterization data can be examined, perhaps with a chi-square test, to see which type of distribution fits best.

4.3.3.5 Ramifications to variables tests. As in the case of attribute tests, there are many ramifications to the use of variables tests. In some cases (e.g., step-stress tests) the uncertainty in the measured parameter or stress can be of importance. In other cases a two-sided tolerance limit may be of importance. Because military device specifications use attribute sample size series tests almost exclusively, this document will not address the ways in which variables tests may be used. It should be recognized, however, that, when systems require very high piecepart survival probabilities, variables tests for lot acceptance may become necessary.

4.3.4 Sampling statistics. The word confidence, as used here, refers strictly to sampling statistics and is the chance of rejecting a lot where there is less than a probability P that any part in the lot can pass the test conditions. The general practice is to take this confidence as the confidence that shipments will be acceptable. This latter use of the word confidence is a matter that is being discussed in the still somewhat controversial subject of Bayesian statistics and is beyond the scope of this document. The important point is that the latter confidence may only be approximated and involves judgmental decisions. A common practice in hardness assurance is to take the sampling statistics confidence as the confidence that accepted parts will survive. This is an approximation which, though usually valid, may sometimes lead to error. Perhaps the best justification for such an approximation is that it is usually not the major factor which limits the accuracy and confidence levels associated with system survivability estimates and risk assessments. Often, a more difficult problem, for example, is simulation fidelity (does the test accurately represent the threat environment that is specified for the system).

4.3.5 reasonability of risk assessment results. The major point of the above discussions is to show the approximate nature of risk assessment. Excessively high survival probabilities, such as, for example, a survival probability of 0.999999 (so called 6-nines) may be unreliable for a number of reasons. First of all, such numbers can only be obtained from extrapolations based on an exact knowledge of the probability distribution. However, because radiation tests use modest numbers of parts and the parts which are tested cannot be used afterwards, knowledge of the assumed probability distribution is never adequate for such extrapolations. Thus, for example, some accidental occurrence during the production of the parts may, with a probability exceeding 1 minus 0.999999, produce a part which does not fit the probability distribution assumed

for the majority of the parts; the presence of such parts cannot be detected with confidence by the sample sizes which are typical of radiation tests. At the 6-nines level also, human errors in making measurements or in handling the parts can become a significant failure mode which is totally outside the assumed causes of part failure.

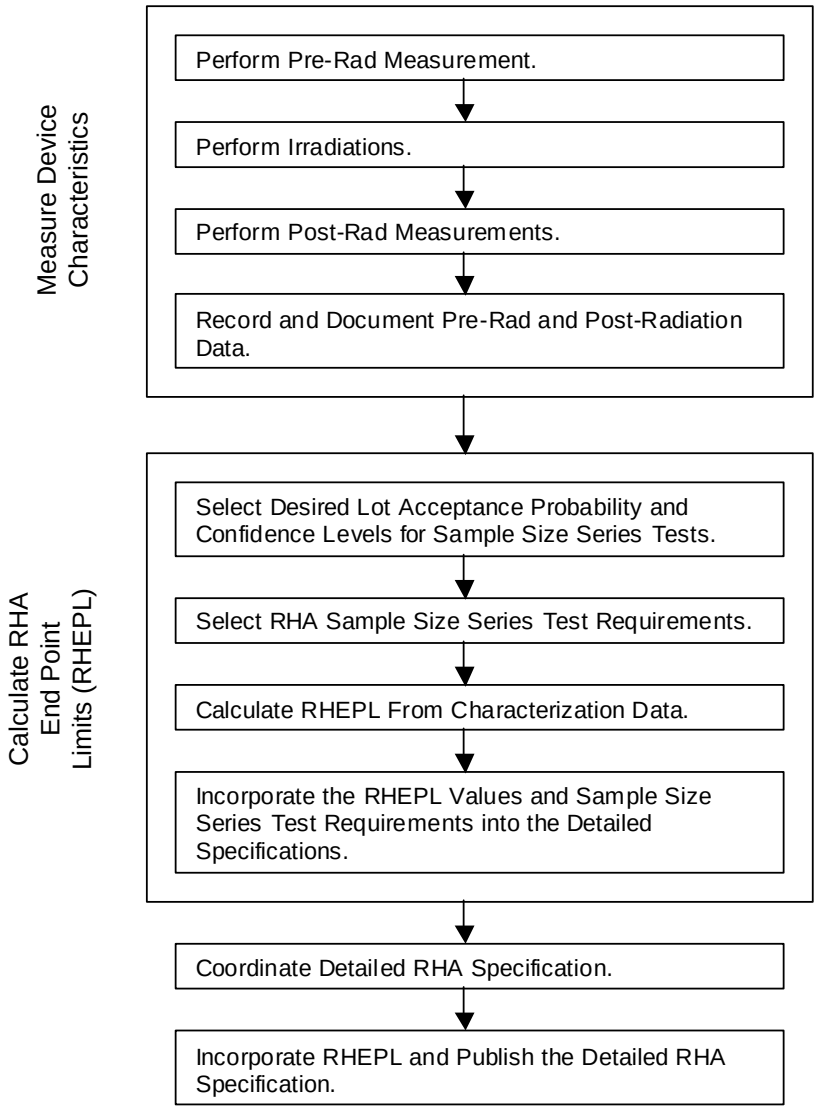

FIGURE 2 Flow diagram for characterizing and specifying the performance of semiconductor devices in a radiation environment.

4.4 Part characterization. Figure 2 shows the major steps by which characterization data is measured and used for calculating the RHEPL which are then used in the device procurement specification for radiation qualification and LAT. An important point shown on figure 2 is that an objective must be selected for the LAT (or QCI) tests and that the RHEPL are then calculated to meet that objective (the acronym PIPL, standing for post-irradiation parameter limits, is also used). Thus, for example, the objective could be to set the end-point limits so that, with 90 percent confidence, at least 90 percent of future lots may be expected to pass a 22/0 test. Pre-rad measurements are essential when the change (delta) in the value of a parameter is of greater interest than the absolute value of the parameter. Although they may not be essential when the

absolute value of the parameter is the important quantity, they are nevertheless highly desirable. Figure 2 and subsequent discussions, therefore, include pre-rad measurements as part of the characterization procedure.

4.5 Considerations beyond the scope of this document.

4.5.1 Incorporating additional radiation and nonradiation information. If information is obtained in addition to that provided by the given Sample Size Series test against the RHEPL contained in the detailed device specification, then, for particular system applications, there are several methods by which RHA part survival probabilities can be obtained which are higher than those which correspond to the Sample Size Series test alone. These methods include: The use of the next higher radiation level RHA part, radiation overtests, the use of lot rejection information, the use of variables testing for LAT, and the use of derated parameter values. As an example, most systems manufacturing companies are already familiar with the use of derating factors for temperature and aging. Radiation derating factors may be used in much the same way and can thus be fitted into existing practices. These methods properly belong in a document on system level hardness assurance and are not further addressed here.

4.5.2 Further complex questions. The statistical questions involved in hardness assurance and lot acceptance tests range in complexity from cases for which the analysis methods are relatively straightforward to those for which the required formalism is still being developed. In the former instances, these guidelines provide simple step by step procedures that may be used for the analysis of the characterization data. In the latter instances, which are beyond the scope of this document, these guidelines can only suggest approaches which are overly conservative or recommend that statisticians be consulted for less conservative but still valid analyses. In the latter category are cases where the within-lot variations are comparable to lot-to-lot variations (in this case the definition of sample size can become uncertain), cases of combined environments or combined parameters, and cases where not enough data is available. The 1987 paper by Namenson and Arimura, listed in 2.2, may be consulted for an approach to multi-lot and multi-parameter data analysis.

5. DETAILED REQUIREMENTS

5.1 Characterization of piecepart performance in radiation environments (see figure 3). The first step required for developing a device specification is to characterize the radiation response of the part type in question. Such a characterization for one or more radiation environments requires measurement of its post-irradiation performance and, usually, its pre-irradiation performance as well. The parts, generally, should be characterized through to failure so that the specifications can be written, if necessary, for the maximum capability of the part type. For the present discussion it is assumed that the purpose of the characterization measurements is to support the calculation of parameter end-point limits for qualification and LAT tests in a military standard detailed specification and that satisfactory data for the part type in question does not already exist. In this case, the characterization measurements should be such as to permit these calculations to be made for the radiation levels given in table I. Alternatively, the characterization measurements may be required in direct support of a hardened system design or production (custom specifications). In this latter case, the parameters which are measured and the types and fluence levels of the radiations which are used should reflect the system requirements and the specific vendors who are expected to be suppliers for the system. The characterization measurements should also determine the radiation levels required to cause part failure; such information can be important for estimating the design margin when the part is used in some particular application.

To simplify the present discussion, we assume that the average post-irradiation performances of a part type may differ for different manufacturers and, for a given manufacturer, may differ from one lot to another, but that the average radiation response characteristics of a part type, for a given manufacturer, do not significantly change with time. This latter assumption may not always be warranted. It is needed to keep the initial discussion of data measurement and analysis free of the additional complexities that time variations produce.

5.1.1 Documentation of characterization information. Experience has shown that the analysis of radiation data at a future time or by persons other than those who performed the measurements is enormously facilitated by good documentation of the test results. At the same time, a need to analyze previously acquired data or data acquired by others is common. For these reasons and because new measurements are costly, these guidelines recommend that the overall characterization measurements be summarized in a characterization report and that the conditions under which the measurements were made be documented in a test plan which is included in the characterization report. These documents should furthermore be sufficiently complete so that independent data analyses can be performed on the results contained therein.

5.1.2 Selection of manufacturers. For a selected part type, the potential manufacturers to supply that part for government procurement should be identified. If the part type is already a JAN type or SMD, the respective QPL or QML will serve as a starting point. DSCC and the preparing activities for the military standard procurement system (SPAWAR, and NASA) should be consulted, however, to learn whether additional vendors might be in the process of qualifying for that part type. If the part in question is to be supplied to a Standard Microcircuit Drawing (SMD) or other government specification, then the list of vendors will need to be obtained either from DSCC or the cognizant project office.

5.1.3 Selection of random test samples. Sample parts for testing should be selected at random. Because of cost, part availability, schedules, etc., it may not always be practical to obtain an adequate set of samples. The procedures discussed under data analysis in 5.2.4, will still apply but will produce increased uncertainties in the results which will reflect the inadequacy of the sample of parts which was used for the characterization. One way of saving costs might be the use of parts which have passed group A electrical performance tests and alternate visual criteria; this possibility is mentioned for VLSI parts in particular but could have application whenever the cost of sample parts is a limiting factor. It is always advisable that the test parts have gone through burn-in.

5.1.4 Obtaining samples. Once the vendors have been identified, samples of parts should be obtained from each vendor. For each vendor, the samples need to be taken in random fashion from each lot of parts that is being used and the lots need to be selected so that they represent, as accurately as possible, production characteristics. The production variations which are of concern are: (a) variations over time, (b) variations from one wafer lot to another, (c) variations from one wafer to another in a wafer lot, and (d) variations of the devices from one region of the wafer to another.

A few extra samples should be obtained to cover the possibility that some devices may, in later measurements, prove to be either bad devices or outliers which will need to be replaced.

5.1.4.1 Recommended sample size. To meet the concerns listed in the previous section, the following quantities, for each vendor and for each radiation environment, are recommended:

a. Three wafer lots taken at least 1 month apart.

b. Five wafers per wafer lot.

c. Five devices per wafer taken one from each quadrant and one from the center.

A few extra samples should be obtained to cover the possibility that some devices may, in later measurements, prove to be either bad devices or outliers which will need to be replaced. See 5.2.4.1.1 for a discussion of bad devices or outliers.

5.1.4.2 Reduced sample sizes. It should be understood that, in cases where the recommended quantities prove to be impractical because of cost or schedule impacts, the vendor may propose reduced sampling requirements. Reduced requirements may be acceptable, for example, where data exists showing the radiation response of the part type in question to be stable and predictable over long periods of time or that the part response will be similar to that of another part.

5.1.4.3 Minimum sample sizes. The sample size recommended in the previous section, for each vendor and radiation environment, is a total of 75 devices. If that number of devices cannot be made available, then reduced sample sizes will have to be considered. Roughly speaking, 25 is the minimum sample size which should be used for a characterization measurement, the more parts the better. For this minimum sample size, the recommendation is that five different lots be sampled and that five samples per lot be taken. A sample of 25 will at least allow a goodness of fit test to determine whether the parts' behavior belongs to a well defined statistical distribution. If the relevant parameters degrade gracefully with radiation and if the probability distribution is known well enough, then five or even as few as three parts from each lot might be adequate. Larger sample sizes will reduce uncertainties about the nature of the governing probability distribution and will thereby permit better performance estimates for the parts remaining in the population from which the sample was drawn. Sample sizes which are too small may result in characterization data with large statistical uncertainties. These uncertainties can result in overly conservative decisions about how the part should be used or purchased and may lead to costs which will more than undo the savings produced by the small sample size. No simple prescription for selecting sample size can be given. Relevant factors, in addition to part cost, which will affect how large the sample size should be (for each vendor), will include the amount of previous knowledge available about the part and the variability of the parts' performance on a single wafer, within a wafer lot, and from lot to lot. If lot to lot variability is large compared to variability within one lot (a

not uncommon occurrence) then, in the data analyses that are performed, the sample size effectively becomes the number of lots and not the number of parts tested.

5.1.4.4 Sample sizes in characterization report. The number of samples to be tested, for each vendor, is to be included in the characterization report and in the test plan.

TABLE III. Device identity information.

a. Device identification number b. Generic part number c. JAN part number (if applicable) d. Name of the manufacturer e. Lot date code f. Lot number (wafer lot number, if applicable) g. Wafer number (if applicable) h. Serial number (for each device) i. Package type j. Special selection criteria (if applicable)

5.1.5 Device identity number and pedigree. Serious problems in analyzing data have also been experienced because the device that was tested was not adequately identified. The information needed to establish an adequate device identity is shown in table III. This information should be recorded in the characterization report. As discussed in 5.1.7.5 on data format, a subset of the table III information should be included when the actual test data is recorded and tabulated in the characterization report. It should be recognized that radiation response characteristics, especially for ionizing radiation dose, can be very sensitive to processing conditions. Thus, to the maximum extent practicable, all processing steps and equipment should be documented for the lot under test. Whenever possible also, the lot under test should be a wafer lot, because a wafer lot is defined as one for which all processing steps are the same and performed with the same equipment. In the case of JAN class S or MIL-PRF-38535, class V devices, wafer identity is also available and should be recorded.

5.1.6 Selection of radiation environments. The characterization report and the test plan should identify the radiation environments, such as neutrons; ionizing radiation dose (total dose) and dose rate, also the type of radiation, i.e., whether electrons, gamma rays, protons, etc., and heavy ions or protons SEU, the radiation facilities, and the levels that will need to be used for the testing. This step should precede that of selecting the test parameters to ensure that no parameters are overlooked which might be especially sensitive to a particular radiation environment. For the two radiation environments of principal interest here, namely neutrons and ionizing radiation dose, the effects are expected to be independent and characterization measurements can be made separately for the two environments. If the effects from two environments are expected to depend on each other, as for example, temperature effects on dose rate induced latch-up, or ionizing radiation dose effects on SEU sensitivity, then each part will have to be exposed to both environments. If the given part type is known to be very hard to a particular radiation environment as, for example, an MOS device may be to neutrons, then characterization measurements for that type of radiation may be omitted. Careful consideration should be given, however, to the possibility that intentional or parasitic sensitive elements (e.g., bipolar devices in the MOS example cited) may be present in the device.

5.1.7 Selection of test parameters. All the parameters that are to be measured need to be selected and listed in the test plan. Normally, for QML parts, the subset of group A electrical parameters that are known to be sensitive to the selected radiations will be used. In some instances, the change in the value of a parameter is more significant than the absolute value of the parameter. For those cases, the test plan should specify that the change, or delta, in the parameter value be measured.

5.1.7.1 Test conditions and parameters to be recorded. The parameters or circuit functions that need to be measured will have to be identified and listed in the report and in the test plan along with the experimental conditions under which the measurements are to be made. The specified conditions should include both the nominal and the worst case conditions under which each parameter should be measured. They should also include such quantities as, bias voltages, operating frequencies, and ambient temperatures before, during, and after irradiation. For the worst case measurements, the report should contain recommendations on how such conditions

may be derived or at least bracketed (circuit analyses may be required to arrive at worst case conditions). This section of the report may also be used to identify, for each parameter that is to be measured, what value of the parameter constitutes device failure. Such definitions are needed in connection with the fluence to failure measurements recommended earlier for permitting estimates of design margin to be made for particular applications. Failure may be either parametric failure, loss of functionality, or degradation to the point where the device can no longer be used.

5.1.7.2 Objectives of the test conditions and parameters. The selection of test conditions and test parameters will depend on the objectives of the test, time and budget constraints, and, possibly, other factors. For each test, however, the information listed in table IV should be recorded in the characterization report. As is discussed in 5.1.7.5 on data format, a subset of the table IV information should be included when the actual data is tabulated and recorded in the characterization report. Experience gained by the DNA sponsored ERRIC is the basis for most of the recommendations contained in these guidelines regarding data requirements and format.

5.1.7.3 Narrative information. The narrative information listed in the table IV is used to provide a further description of the device and the test conditions required for each test.

5.1.7.4 Symbols. A partial list of military standard symbols for particular device parameters and the corresponding symbols used by ERRIC is given in appendix A. A standard list which all users have agreed to use does not exist for device parameters. As a result, different symbols are sometimes used by different organizations for the same device parameter. ERRIC can receive data labeled in any way and uses a narrative comment as part of the data storage to make sure the device parameter is properly identified. If data processing programs are used for analyzing the behavior of particular parameters, provision should be made for recognizing some limited set of the symbols for the parameter in question in addition to those given in appendix A.

5.1.7.5 Specification of a data format. Although data format would appear to be a simple matter, past experience has shown that severe difficulties can be encountered, particularly with computerized data analysis programs, if a standardized data format is not used to record the data. Because the accumulation of radiation response information in a centralized data bank can help avoid duplication of such measurements and is therefore highly desirable, the data format recommended here is the one used by ERRIC.

TABLE IV. Pre- and post-irradiation measurement information.

a. Name and organization of test engineer.
b. List of equipment used for measurements and calibration procedures.
c. Description of test procedures or test standards used.
d. Electrical test date.
e. Test number.
f. List or table of electrical test parameters and corresponding bias conditions; (note that the pre-rad bias conditions should be used for the post-rad measurements)
g. A complete time history of the individual irradiations and the post-irradiation measurements (especially necessary for ionizing radiation dose (total dose) because of time dependent effects)
h. Ambient and/or case temperature.
i. Sample size.
j. Electrical measurement results for each parameter.
k. Narrative information.

5.1.7.5.1 Definition of a test number in ERRIC. In ERRIC, a unique test number is assigned to both the pre- and post-rad measurements that are made on a single parameter under a single set of bias or operating conditions, for all devices in the sample, and for all the radiation fluences used. The information which is common to a unique test number and which can be used therefore as the heading for that test number is listed in table V. Pre- and post-rad test results obtained for all the sample devices that are covered by the same heading are then listed under a single test number. Table VI shows an example of how ERRIC data is recorded. For test number 2 and subsequent tests made on the same devices and for the same irradiation conditions, the first three lines of the heading need not be repeated. Thus, the data for test number 2 could be recorded as in table VII.

TABLE V. Example of ERRIC test data.

Test number: 1 ; Test date: 10-21-85

Type of radiation: Neutrons; Radiation facility: PMI

Device type: DAC-08; Manufacturer: ABC; Lot date code: 8429

Parameter: IREF; Units: mA

Test conditions and narrative information:

a. Bit high speed multiplying D/A converter (device description included only for test number 1).
b. Reference bias current (parameter description).
c. V+ = 15 V, V- = -15 V.
d. Measured 24 hours after the end of the irradiation.

Measurement data

Device serial number	Radiation level PRE-RAD	2.00E12	6.00E12	1.00E13
0271	2.00	2.00	2.00	2.00
0272	2.00	2.00	2.00	2.00
. . . .	. . . .	. . . .	. . . .	. . . .

TABLE VI. Information common to a unique test number in ERRIC.

a. Single type of radiation and corresponding test facility
b. Single part type
c. Single manufacturer
d. Single test date (post-rad)
e. Single lot date code
f. Single wafer lot number (if available)
g. Single parameter measured and associated bias or operating conditions
h. Narrative information (should include information about the irradiation conditions and time history of the irradiations and the electrical measurements)

5.1.8 Test plan. Figure 3 (see 5.1.1.1) and table II (see 5.1.1.1) show the major steps involved in characterizing the radiation response of a part. Also shown are the steps which are included in the test plan. The test plan should, as a minimum, address the pre-irradiation measurements to be made, the irradiations to be performed, the post irradiation measurements to be made, and, finally, should specify the data documentation requirements and format.

5.1.8.1 Advantages of a good test plan. The development of a detailed test plan is recommended as a way to make characterization measurements efficient. A good test plan will minimize costs by specifying the data set which will meet the objectives of the measurements and by optimizing the use of radiation test facilities and part samples. The test plan should also facilitate subsequent data analysis by specifying a data format which will be easy to use and will protect against inadvertent omission of required data points by providing a check list for the measurements.

TABLE VII. ERRIC data format for test number 2 in a series.

Test number: 2 ; Test date: 10-21-85
Repeating test information: Same as lines 2 and 3 for test number 1
Parameter: IZS; Units: mA
Test conditions and narrative information:

a. Zero scale current (parameter description)
b. V+ = 15 V, V- = -15 V.
c. Time of measurements referred to the end of the irradiation.

Measurement data

Device serial number	Radiation level Pre-rad	2.00E12	6.00E12	1.00E13
0271	4.20E-5	2.00E-5	6.50E-5	1.67E-4
0272	-2.00E-6	4.70E-5	9.00E-5	2.54E-4
. . . .	. . . .	. . . .	. . . .	. . . .

5.1.8.2 Pre-irradiation measurements and data examination. If the pre-irradiation characteristics are measured, the measurements should be made according to the conditions listed in table IV (see 5.1.7.2) and recorded in the format given in table VI (see 5.1.7.5.1) and table VII (see 5.1.7.5.1). The data should be examined to make sure that there are no bad measurements, devices or data outliers in the sample. This examination is important to keep bad data from being entered into the report. If bad or anomalous data are taken, this fact together with an explanation of why the data is not being used should be recorded in the characterization report even if the data are not sent to ERRIC or some other data bank. The annual books of ASTM standards, listed in 2.2, contain many of the test methods that can be used for making radiation response measurements.

5.1.8.3 Caution. Caution should be exercised when devices are handled, particularly with regard to pin alignment in the holding fixture and when the devices are attached to the test circuit. Bias voltages should be off during attachment. ESD handling procedures should be observed for the class of parts being tested.

5.1.8.4 Irradiation conditions. The irradiation conditions and the reasons for selecting them should be discussed in detail in the characterization report and summarized in the test plan. The information to be included in the test plan is listed in table VIII. The various questions that need to be addressed in selecting the irradiation conditions are discussed in the sections which follow. For each of the selected radiation environments, the plan should include the test facility selected, the responsible organization and personnel, recommended dosimetry techniques, the maximum fluence or ionizing radiation dose to be reached (whenever possible, the radiation levels should be high enough so that most of the test devices can be made to fail), and whether device measurements will be made “in-flux”, i.e., while the device is being irradiated, or whether a series of discrete irradiations with measurements following each irradiation will be made. In the latter case, which is sometimes called step stress testing, the test plan should specify the number of irradiations to be made and the ionizing radiation dose or fluence for each irradiation in the series. Because time dependent effects can be very important, especially for ionizing radiation dose, a complete time history of the irradiations and the post-irradiation or in-flux measurements should be recorded. This time history should include the start and stop times of both the irradiations and the measurements as well as the rate at which the ionizing radiation dose was delivered. The test plan should state, whenever possible, that a standard irradiation test method should be used and give the appropriate reference.

TABLE VIII. Irradiation conditions.

a. Name of the radiation test facility. b. Name and organization of radiation test engineer. c. List of dosimeter types and readout equipment. d. Date of irradiations. e. Irradiation run number. f. Number of samples in each irradiation. g. Placement of samples with respect to the radiation source. h. Radiation facility operational mode. i. For each irradiation, flux or dose rate, fluence or ionizing radiation dose, start and stop times, and ambient or device case temperature. j. Device bias conditions and whether in-flux measurements will be made. k. Start and stop times for post irradiation measurements, including measurements made during a series of radiation exposures (particularly important for ionizing radiation dose because of the time dependent effects which can occur).

5.1.8.5 Estimates of device failure levels. To reduce costs and to optimize the usefulness of the data obtained, it is important to estimate the expected failure levels for the selected device type and radiation environment before full scale characterization measurements are begun. Device failure will usually be defined as parametric failure but may sometimes be defined as functional failure. In the case of parametric failure, it is well known that different failure limits can be defined for different device applications. For the present purpose, engineering judgment should be used to define a failure limit for each parameter being measured. The important point is that the lowest stress level which renders the device unacceptable should be considered as the failure level. Estimates of failure levels will have to be based either on previous experience and data or on measurements on a few parts from the available samples. The steps by which the failure points are estimated should be documented in the characterization report. Because the definition of parametric failure depends on the intended device application, the estimated failure points will only be approximately correct. They will nevertheless be useful for adjusting the irradiation increments and the total fluences to match the expected device performance. The irradiation increments and the total fluences selected on the basis of the estimated failure points should be listed in the test plan. After the characterization measurements are completed, device failure points can be more accurately defined.

5.1.8.6 Gradual degradation. For devices which degrade gradually as they approach failure, it will generally be useful to measure post-irradiation performance characteristics as a function of accumulated radiation fluence or ionizing radiation dose because such results can be used to interpolate or, in some cases, extrapolate the part's performance to radiation levels other than those used in the tests. For such devices, the number of irradiations and the radiation increments should be made commensurate with the expected failure levels. It is worth noting that a gradual approach to failure may not always be monotonic; sometimes a parameter may first increase with radiation fluence and then subsequently decrease. This behavior means that, in the military standard system and for the radiation levels shown in table I (see 4.2), a part type that has been qualified at a higher level may not meet the same RHEPL at a lower level. Qualification at a higher level should therefore not mean, automatically, that the part is also qualified at a lower level unless care is taken to select the RHEPL so that it does not show less degradation at the higher level.

5.1.8.7 Abrupt failure. Some devices give little or no indication that a radiation failure point is being approached, until they fail abruptly; usually abrupt failures occur as loss of functionality. The claim has sometimes been made that there is usually some gradually deteriorating parameter which can be used as a predictor of abrupt failure (e.g., a flip-flop circuit failing functionally when the fanout capability of the circuit, as indicated by the sink current, degrades past a certain point). As a practical matter, however, a device must be considered to fail abruptly when there is no feasible way to pin-point its failure level by means of interpolation. An estimated failure level is also important for such devices and should be used for selecting the number and increment value for the irradiations such that the abrupt failure point will be narrowly bracketed. Whenever possible, the most desirable measurement is to monitor the device while it is being irradiated to determine the exact stress level where failure occurred. Again, the estimated failure point will have to be based on previous data or on measurements on a limited sample size before full scale characterization measurements are made.

5.1.8.8 Optimum use of radiation facilities. Such factors as the number of devices which can be irradiated at one time, the length of time required for the irradiation, and the length of time required to complete post-irradiation measurements should be considered when an irradiation schedule is being planned. The selected irradiation schedule should then be itemized in the test plan.

5.1.8.8.1 Selection of radiation levels. For each type of radiation and for each estimated device failure level, a series of irradiations should be selected so that data is obtained most efficiently. The lowest level of radiation should be below that which produces any failures. In general the subsequent irradiation increments will be sizeable fractions of the failure level. If significant nonlinear behavior is produced, however, then the location of the nonlinear region must be estimated and the radiation increments should be made smaller than they are outside of it. The highest radiation level should be high enough so that all of the tested parts will fail. This selection will not only allow the device specification to be written for the maximum capability of the part type, should that be necessary, but will provide information on how close the part is to failure for a given system application.

5.1.8.8.2 Selection of radiation levels and abrupt failure. For step stress measurements and the presence of abrupt failure, the proper selection of radiation stress levels is of particular importance because a bad choice can compromise the measurements. The spacing between stress levels should be as small as feasible. At the very least, care should be taken to assure that the spacings are small compared to the estimated standard deviation of the failure fluences for the parts to be tested. An estimate of this standard deviation may not be easy to obtain. As a first approximation, data on similar parts may be used. If there is no suitable data, smaller than expected spacing may be necessary for the first few parts and then, if costs can be lowered thereby, the spacing for the rest of the parts can be adjusted according to the measured standard deviation. For a complete characterization, the highest stress level must be large enough to drive all the tested parts to failure. Very wide stress levels may require an extra large sample size. Less than four stress levels are unacceptable if abrupt failure of devices is considered a possibility.

5.1.8.9 Efficient use of test samples. The costs of radiation testing and, for some part types, the cost of the parts themselves both provide strong reasons for keeping the number of test parts as low as possible. In these circumstances it is essential that the experiments be specifically planned so that the maximum amount of useful information is obtained from the sample size that is available. Whenever possible, preparations for the actual tests should be conducted on spare and perhaps less expensive parts which are not part of the final sample.

5.1.8.9.1 Selection of exposure sequences. Because most characterization measurements are destructive, a single device is exposed to only one radiation environment and the exposure sequence simply proceeds from low levels to functional or parametric failure. The cases where one device can be used for two radiation environments are those when the dose rate upset threshold measurement, which can be non-damaging, is made first and is followed by neutron, gamma ray, or SEU tests. In these cases care must be taken to ensure that the accumulated ionizing radiation dose in the dose rate testing has not appreciably changed the characteristics of the device. The use of one device for two radiation environments is not recommended. It should be considered only when sample costs are so high that every possible way of conserving sample size must be used. Time dependent effects should be considered when a series of exposures is being planned.

5.1.9 Radiation exposures. Radiation exposures should be made in accordance with the test plan and should contain at least the information listed in table VIII (see 5.1.8.4). Initial test system checkout, e.g., of test equipment operation, dosimetry, etc., should be accomplished with parts which are less costly and readily available; one possibility is to use parts of the same type as the sample but selected to a less stringent visual criterion. The use of a commercial equivalent device type can also be considered but such use will need to be validated experimentally.

5.1.9.1 Neutron exposures. Neutron exposures can be made either at fast burst reactors or at water moderated reactors. In either case, the dosimetry practices at the selected facility should be checked to make sure that a valid 1 MeV displacement damage (Si) equivalent fluence can be obtained (see ASTM E722). Test method 1017 of MIL-STD-883 can be used as a guide for the exposure procedure. Short term (of the order of seconds) annealing effects do not have to be evaluated on QML part types.

5.1.9.2 Ionizing radiation dose (total dose) exposures. Test method 1019 of MIL-STD-883, entitled “Ionizing Radiation (Total Dose) Test Procedure”, specifies Co-60 as the radiation source to be used for ionizing radiation dose testing. Ionizing radiation testing can also be performed with Cesium-137 sources and with low energy x-ray sources. If a source other than Co-60 is used, correlation measurements must be performed to effect a comparison with Co-60. High energy electron Linacs are not recommended because of the

possibility that the displacement damage which high energy electrons produce may interfere with the measurements. Flash x-ray sources which, typically, deliver the dose at a very high dose rate, are not recommended because the results may be difficult to compare with Co-60. Low energy x-ray sources are not recommended for characterization measurements unless a valid correlation to Co-60 is established.

5.1.9.3 Bias. Bias must be applied on the device during the irradiations and the bias conditions must be in accordance with the test plan. If measurements are to be made “in flux,” then the test plan should specify these conditions as well. Because time dependent effects can be very important for ionizing radiation dose, a complete time history of the irradiations and the post-radiation or in-flux measurements should be recorded. This time history should include the start and stop times of both the irradiations and the measurements as well as the rate at which the ionizing radiation dose was delivered. A pre-test evaluation of the time dependent effects may also be necessary to make sure the times used for the irradiations and the measurements will give meaningful results.

5.1.9.4 Transient ionization (dose rate) exposures and measurements. High energy electron Linacs are the facility of choice for dose rate upset measurements. If flash x-ray machines are used, extra care is required with the dosimetry to make results obtained at one facility comparable to those obtained at another.

5.1.9.5 Single event effects irradiations and measurements. SEE measurements are sufficiently complex so that they should be made in collaboration with one of the several groups in the U.S. that are making such measurements routinely. A full characterization measurement for single event effects produced by heavy ions requires that the number of upsets or the latch-up in a particular device be measured as a function of the Linear Energy Transfer (LET) of the ion. Heavy ion irradiations are usually performed at cyclotrons or at Tandem Van de Graaff accelerators but may also be performed at other high energy heavy ion accelerators (see ASTM F1192, EIA/JEDEC-57, JESD-89). For single event upsets induced by protons, a measurement of the number of upsets per unit fluence at a proton energy of 60 MeV or higher should be adequate as an input data point to a theoretical model that can then be used for estimating the total number of device upsets to be expected in some particular proton environment. (See Bendel and Petersen, 1983.) High energy protons for SEE tests can be obtained from a number of cyclotron accelerators. Laser and Californium-252 techniques are being studied but have not yet advanced to the point where they can be used routinely for SEE characterization measurements.

5.1.10 Post-irradiation measurements and data examination. The parameters which will be measured after irradiation and the measurement conditions, and the equipment if possible, should be the same as those for the pre-irradiation measurements. Table III (see 5.1.5) and table V (see 5.1.7.5.1) list the information required. The test plan will contain the actual parameters to be measured and the corresponding operating conditions. However, the post-irradiation measurement procedure will have to take into account the possibility of time dependent effects. In the case of ionizing radiation dose, time dependent effects can be especially serious and must be evaluated for the device being tested. MIL-STD-883 or MIL-STD-750 method 1019 can be used as a guide until an improved method for taking time dependent effects into account is developed. Bias must be applied during the irradiation. Bias may not be necessary at all times after the irradiation but the bias conditions and other measurement conditions and time intervals should be as consistent as possible from one run to another. Bias or shorting conditions on the device between the end of a radiation exposure and the start of electrical measurements should be recorded. Again, the measurement results should be examined for bad devices or outliers and, appropriate action taken if necessary. This examination is important in preventing bad data from being included in the characterization report and, possibly later, from entering a database.

5.1.11 Data recording. Table IX gives a summary of the recording requirements for the test plan.

TABLE IX. Summary of data to be recorded in the test plan.

Pre-rad measurement conditions: Items in table IV.
Irradiation conditions: Items in table VIII.
Post-rad measurement conditions: Items in table IV.
Data recording: As in table V, table VI, and table VII.

5.1.12 Performance characterization report (see table X). An essential part of any characterization measurement program is to document all the measurement results completely enough so that another investigator can use the results without having to consult the originator. For a variety of reasons, time and funding being principal among them, this task is often not performed adequately. The importance of the documentation task, however, cannot be overemphasized. The hope here is that if the documentation task is made part of the test plan so that it must be included in any checkoff list or, perhaps, in the contract data requirements list that is part of all government contracts, then the results of characterization measurements will be more available to other users in the future than they have sometimes been in the past.

5.1.12.1 Standard data format. The characterization report should use the standard data format discussed in 5.1.7.5. The recorded data should include the device identity information listed in table III (see 5.1.5) and the test conditions listed in table IV (see 5.1.7.2).

TABLE X. Summary of information to be recorded in the characterization report.

Device identity: Items in table III and corresponding discussion.
Pre-rad measurement conditions: Items in table IV and corresponding discussion.
Irradiation conditions: Items in table VIII and corresponding discussion.
Post-rad measurement conditions: Items in table IV and corresponding discussion.
Data recording: As in tables V, VI, and VII and corresponding discussion.
Final results: Items in table IX and corresponding discussion.

5.1.12.2 Transfer of characterization data to ERRIC. To make as much radiation response data as possible available to U.S. users, the Defense Threat Reduction Agency (DTRA) supports a data bank for such data at the ERRIC operated by the Defense Threat Reduction Information Analysis Center (DTRIAC). The collection is stored in a Visual FoxPro database to allow more versatile and user-friendly queries. It is on-line, using Windows NT as its operating system, along with FoxWeb as its interface via the Netscape commerce server. The URL is: http://erric.dasiac.com. ERRIC is actively collecting data from other data banks and is very much interested in receiving any new data that is taken. It is strongly recommended here, therefore, that the characterization data which is obtained and documented in the characterization report also be sent to ERRIC. ERRIC is equipped to acquire data from computer disks as well as in printed form. The address and telephone number for ERRIC are:

ERRIC
The Defense Threat Reduction Information Analysis Center
ITT Industries, Advanced Engineering and Sciences Division
2560 Huntington Avenue
Alexandria, VA 22303-1410
(703) 329-3872

5.2 Calculation of electrical parameter end-point limits. The previous sections of this report have described how radiation response characterization measurements should be made so they can be used for defining lot acceptance tests that will provide hardness assurance in future procurement. At this point the assumption is made therefore that the characterization results have been obtained and the discussion turns to the procedures by which lot acceptance tests should be defined. The basic goals here are to select the sample size and to calculate post irradiation test criteria from the characterization data such that future radiation lot acceptance tests performed against these criteria will meet a selected objective. Typically, the selected objective will be a desired lot acceptance probability and confidence level.
It is worth noting that the methods described here are not limited just to radiation hardness assurance but can be used for the more general problem of calculating end-point limits to meet a selected lot acceptance objective. They may be of use, therefore, to any manufacturer of parts who is interested in quantifying the lot acceptance results he can expect as a function of the end-point limit or specification value he selects for a given parameter.

5.2.1 Lot acceptance tests. Lot acceptance tests are based on testing a sample of parts after they have been irradiated and determining whether the sample of parts passes or fails some specified criterion. If a variables test is being used then the measured mean value and standard deviation of the post-irradiation parameter values will be compared to the specified criteria to determine whether the test passed or failed. If an attribute test (such as a sample size series test) is being used, then specified RHEPL and, possibly, functionality, will be used for determining whether each part, individually, has passed or failed the test. Changes or “deltas” in a parameter may also be used as a RHEPL.

5.2.1.1 Attribute lot acceptance tests in military standard procurement. Because military standard procurement rely almost exclusively on attribute tests, the discussion here mostly addresses this type of test. It should be recognized, however, that, for the same number of samples tested, radiation lot acceptance tests based on variables measurements will usually give higher quality results. Their principal disadvantages are that they are somewhat more complex and costly and require assumptions about the probability distribution to which the parts belong. Attribute tests such as the sample size series tests used in the MIL-STD system have the advantages that they require less documentation of test results, do not require as much training for test personnel, and do not depend strongly on assumptions about the probability distributions to which the tested parts belong. The relative merits of these two types of tests were discussed in some detail in the forward.

5.2.1.2 End-point limits for sample size series tests. Figure 4 shows the steps to be taken for calculating end-point limits for sample size series lot acceptance tests. Table XI lists these steps in finer detail as a step-by-step check off procedure.

TABLE XI. Step by step procedure for calculating end-point limits.

Step	Check-off item
1.	Select device type and manufacturers.
2.	Obtain characterization data and documentation.
3.	Select desired lot acceptance probability, confidence level, and sample size for sample size series tests.
4.	Select parameters to be tested and test conditions.
5.	Begin data examination.
6.	Check data for sufficiency.
7.	Check for outlying devices.
8.	Check for outlying lots.
9.	Discard outliers.
10.	Check data for abrupt failures.
11.	If abrupt failures have a significant likelihood, parameter end point limits usually cannot be calculated.
12.	Check for unexpected functional dependencies.
13.	Check for systematic or nonrandom effects.
14.	Check for correlations with respect to time of manufacture.
15.	Check for unexpected magnitudes of lot-to-lot variations.
16.	Check for bad data points.
17.	Correct or discard bad data points.
18.	Check data for sufficiency.
19.	Recast the data to the specified conditions.
20.	Determine within-lot and lot-to-lot variations.
21.	If within-lot variations are larger than lot-to-lot, use case 1 analysis method to calculate the RHA end-point limits (RHEPL).
22.	If within-lot variations are smaller than lot-to-lot, use case 2 analysis method to calculate the RHEPL.
23.	Incorporate the RHEPL and sample size series test requirements into the device specification.

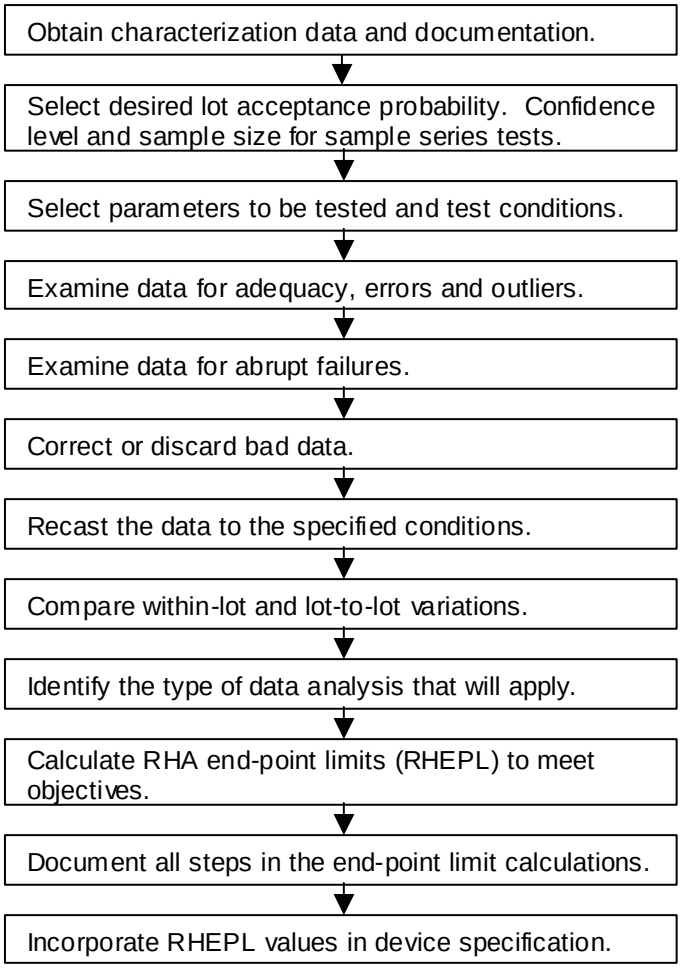

FIGURE 4. Steps for calculating end-point limits for lot acceptance tests.

5.2.1.3 Statistical uncertainties associated with lot acceptance testing. The sample size series sampling table in MIL-PRF-38535, Appendix D and other military standard documents are based on statistical formulas for sampling with replacement i.e., the sample parts used for the tests is replaced into the lot of parts from which it was drawn. Because radiation tests are damaging, the parts tested are not replaced into the lot. The statistical implications of this fact can be complex and are beyond the scope of this document. In general, statistical uncertainties are reduced when the lot acceptance sample size is large and are further reduced if the lot acceptance history is known. The least desirable situation occurs when only a single lot has been tested and when the sample size is only a few parts, say four or less. In this latter case it will be difficult to estimate what the performance characteristics of the passed lot will be. The recommendation is, therefore, that lot acceptance tests based on four parts or less should not be used. For small sample sizes, information about the uniformity of the lots is also very important. If a lot were perfectly uniform, for example, then testing a single part would be adequate. If the uniformity of each lot is high then, during the lot acceptance tests, most of the time, either all the parts pass or they all fail. For such uniform lots, a 2/0 or a 4/0 test (presently specified in the group E tests of method 5005 of MIL-STD-883) may be able to give some confidence that the passed lots are of high quality. If lots are mostly being rejected because one part out of the sample is failing, then the passed lots must be considered to be of low quality.

5.2.2 Definition of RHA end-point limits (RHEPL). The parameter values against which the post radiation performance of a part will be compared to determine if the part has passed or failed the test have been termed RHEPL. These RHEPL values are included in the procurement specification and are used for the lot acceptance tests. If the procurement system uses a qualified manufacturers list or qualified parts list, as, for example, the present military standard specification system does, then these RHEPLs may also be used for part qualification. The discussions which follow explain what decisions must be made before the RHEPL can be calculated and, once the required decisions are made, how they can be calculated from the characterization measurements. If the part can be purchased against any one of several radiation levels, as for example the eight ionizing dose radiation levels, M, D, P, L, R, F, G, AND H, shown for military standard parts in table I (see 4.2), then a separate RHEPL must be calculated for each radiation level. A device can cease to function as a result of a radiation exposure and will, obviously, fail the test being conducted. Such failures are not associated with the definition of an end-point limit. Of course, the functional failure of a part will count as a failure for lot acceptance purposes.

5.2.2.1 One and two sided limits. A parameter used for determining whether a device has passed or failed a test, may be bounded by maximum and minimum values i.e., by “two-sided” limits, or by either a maximum or a minimum value i.e., by a one-sided limit. Because a one-sided limit is the one most commonly used in radiation response testing, only such limits are treated here. The mathematical formulas for the case of two-sided limits are almost identical to the one-sided case so the present discussion can easily be extended to that case if it is necessary to do so.

5.2.3 Criteria for calculating RHA end-point limits (RHEPL).

5.2.3.1 Selection of objectives for lot acceptance tests. Meaningful RHA end-point limits cannot be calculated until the objectives of the lot acceptance testing have been selected. Simply put, if the object of the tests is that at least 90 percent of future lots should pass the test, the end-point limits will be less stringent than if the object is that at least 80 percent of future lots should pass. It should be noted, however, that the statistical uncertainties associated with the relatively small sample sizes that are typically used (tests are usually based on tens of devices but not hundreds) have the consequence that, almost regardless of where the RHEPL is set, there will be a significant probability that a good lot may fail or that a bad lot may pass the specified lot acceptance test. The real constraints on selecting an objective for the LAT and on calculating the corresponding RHEPL, therefore, are the performance of the part and the economic costs of rejecting lots. Thus if the RHEPL is set so that, with 90 percent confidence, 10 percent of future lots may be expected to pass, then the performance of the lots that pass may be very good but the costs of rejecting such a high percentage of lots may make the part too expensive to use. Similarly, if the end-point limit is set so that 90 percent of future lots may be expected to pass, then the cost of the part may be attractive but the performance of the part may not be as good as may be desired. The objectives of the lot acceptance tests are thus seen as a trade-off between passing the largest percentage of lots and keeping end-point limits which will make the performance of the part desirable.

5.2.3.2 Lot rejection probability and choice of end-points. In the data analysis sections which follow, these guidelines show how lot rejection probability depends on the choice of end-point limits. They should, therefore, assist manufacturers or specification developers in selecting end-point limits which best meet their needs. The discussion also shows that lot to lot variability in radiation response can present serious difficulties to end-point limit selection. For this latter case, which is common, the methods recommended here may provide a better assessment of the risks associated with different values of the end-point limits than other methods which have been used.

5.2.3.3 Many parameters and environments. The most tractable case for calculating end-point limits that are to be used for lot acceptance tests is the case of a single radiation environment and a single device parameter. As soon as two or more different and independent test parameters are involved in lot acceptance, then the probabilities of passing for each parameter have to be higher by amounts such that the product of all the passing probabilities equals the probability of passing that is desired. Thus for example, if two different and independent parameters are specified and the desired lot acceptance probability is 0.9, then the respective passing probabilities, P1 and P2, have to be such that (P1)*(P2) = 0.9. The complexities of the calculations for combined radiation environments or parameters or both are such as to put them outside the scope of this document. Unless otherwise noted, therefore, the analysis examples given in the sections which follow are for a single radiation environment and a single device parameter.

5.2.3.3.1 Many parameters. In practice, device specifications generally do have to require that post radiation tests be made on several parameters against specified end-point limits. The recommendation here is that, whenever possible, the characterization data be used to select the most sensitive critical parameter and that the end-point limit be calculated for that parameter to give the desired lot acceptance probability. The end-point limits for the other relevant parameters then must be calculated to give sufficiently high passing probabilities so that those parameters will not cause a significant number of lot failures. Methods are presently being developed to deal with the case when two or more independent parameters have comparable likelihood’s of causing failure but they are not yet in a form which could be included here.

5.2.3.4 End-points and electrical conditions. It is common also for a device specification to give values of a lot acceptance parameter as a function of the operating condition of the device. Thus, for example, end-point limits may be given for the post irradiation gain of a transistor as a function of the collector current. It can then happen, because the calculations are statistical in nature, that different mean values and standard deviations in the characterization data for the different collector currents can result in calculated end-point limits that do not behave in the expected way as function of the collector current. The following caution is therefore advised:

Caution: Data deficiencies and statistical effects or both can lead to end-point limits, calculated as a function of some device parameter, that do not behave in a reasonable way. For example, for a given neutron fluence, the calculated RHEPL for transistor gain may show a decrease with increasing collector current, instead of an increase (in the region below the collector current at which the gain is a maximum). It is important therefore, that the calculated results be subjected to a “sanity check” to make sure that ”unphysical” end-point limits are not entered into the device specifications. In general, a RHEPL should be a smooth function of bias and radiation stress. It should be noted in this connection, however, that a gradual approach to failure may not always be monotonic; sometimes, for example, a parameter may first increase with radiation fluence and then subsequently decrease.

5.2.3.5 Abrupt failures. If abrupt failures are expected to be the dominant failure mode at the radiation levels required for the lot acceptance tests, any parameter end-point limits that are used should be calculated so that they will not cause a significant number of lot failures. This situation resembles that of the several parameters discussed in 5.2.3.3. A method for estimating end-point limits for devices which suffer abrupt failure has been given by Namenson and Arimura (1985); this paper is listed in 2.2. In practice, even though lot acceptance tests may be conducted at a radiation level where some abrupt failures may occur, the subject part type should not be used in a system application if the specified radiation level is such that the likelihood of abrupt failure is expected to be significant; a derating factor of two on the radiation level has sometimes been used but a more accurate value should be based on actual fluence to failure data.

5.2.3.6 Use of end-point limits for system design. Strictly speaking, the end-point limits used for lot acceptance tests do not guarantee how the parts will behave in a system exposed to a specified radiation environment. Nevertheless, systems designers frequently use the RHEPL as the starting point for derating a given parameter for a particular system application. For systems with moderate RHA requirements, the derating may be very small or the RHEPL may even be used directly in the system design. For systems with more stringent RHA requirements, the RHEPL value may be derated significantly or may be set so that only the hardest lots are accepted for system production. Thus, if a part specification is being developed for a particular system, the needs of the design engineer should be considered. The entire topic of lot acceptance and its impact on system design and survivability, while very much deserving of detailed discussion, is beyond the scope of this document.

5.2.3.7 An assumed lot acceptance objective. The many factors involved in selecting an objective for the lot acceptance tests have been discussed in 5.2.3.1. To facilitate the data analysis discussions which follow, the lot acceptance objective is here taken to be that, with 90 percent confidence, at least 90 percent of future lots are intended to pass. This objective means specifically that the end-point limit, which determines the probability, P_S, that a single part will pass the test, must be set so that the probability that the entire test will be passed is 90 percent. This particular objective, in general, does not unduly penalize the performance specifications for a device nor does it place undue requirements on the amount or quality of characterization data. The assumption of a specific lot acceptance objective makes it possible to give actual numerical values for the examples which are to be discussed. The formulas required are given in their parametric forms so that calculations can be made for other lot acceptance objectives.

5.2.4 Data analysis. Because most radiation response results display significant and seemingly random variations, the methods needed to analyze such data are statistical in nature. In addition, most radiation testing involves the use of sample parts which are destroyed by the tests, so the analysis techniques and expectations of future performance (against which lot acceptance parameter end-point limits are calculated) must be based on statistics of sampling without replacement. The sections which follow discuss general analysis principles and their applications but do not attempt to cover all the data analysis variations that can occur in practice.

5.2.4.1 Data examination. A necessary prerequisite for beginning any data analysis, which was mentioned previously but must be discussed in greater detail of its crucial importance, is an examination of the data to ensure that the data do not contain any faulty measurements or nonrandom effects. The data should be examined also for sufficiency. Data examination is all the more important when a significant amount

of time has elapsed between the characterization measurements and the data analysis or when the person or organization undertaking the data analysis is different from the persons who took the data in the first place. Some of the most common reasons for suspecting that data may be bad are discussed below.

5.2.4.1.1 Outlying devices. It is not uncommon, in a batch of measurements, to find that one or more devices out of the sample show failure fluences or post-irradiation parameter values that are significantly outside the values that would be expected from the mean value and variance for the rest of the sample. (Outlying devices may occasionally be found also in the pre-irradiation measurements. The assumption here is that the examination of the pre-irradiation data has eliminated any such devices from the characterization sample.) Although the identification of an “outlier” can sometimes be difficult, a plot of the cumulative probability distribution for the radiation fluences at which the devices fail (or the post-irradiation parameter values) will usually show that the device in question is not part of the population distribution that is characteristic of the rest of the sample. A more detailed discussion of cumulative probability plots may be found in textbooks on statistics. MIL-HDBK-814 also contains an appendix on statistical techniques. A discussion of how to identify outliers may be found in ASTM E178.

5.2.4.1.2 Outlying lots. In this situation, data is available for a number of lots and an examination of the data shows that one or more of the lots are showing an unusual mean value or standard deviation. Again, a cumulative probability plot can be made of the data to evaluate whether the suspect lot or lots belong to a different population of lots.

5.2.4.1.3 Sufficiency of data. The first step in preparation for data analysis is to see if there is sufficient data for deriving end-point limits. The recommendation in these guidelines is that the characterization sample should consist of three different lots taken at least one month apart, with five wafers per lot and five parts per wafer taken one from each quadrant and one from the center. The minimum sample size that is recommended is five different lots with five samples per lot. The data should also contain a range of values and radiation stresses. Thus, for example, if step-stress measurements were performed and all the parts failed in a single “bin” (where a bin is defined as the interval between one fluence and the next higher fluence), there is not enough data for an analysis. If it happens that there is no way to acquire sufficient data, special analysis techniques may be required or some worst case assumptions may be needed to supplement the data. Sometimes it may happen that the number of lots used for obtaining the characterization data is not given in the data. For such cases, a method exists for estimating, from the data itself, what the effective sample size of the device population is and this effective sample size can be introduced into the end-point limit calculations (A. I. Namenson, 1979, see 2.3).

5.2.4.1.4 Abrupt failures. The data should be examined to see if abrupt failures are likely at the radiation levels that will be required for the lot acceptance tests. If abrupt failures are expected to be the dominant failure mode at these radiation levels, then the mean value and the standard deviation of the fluences to abrupt failure in the characterization data should be used to estimate the radiation level at which the part can be used safely. The fluences to abrupt failure are then used to check for outlying devices, outlying lots, and the sufficiency of the data.

5.2.4.1.5 Unexpected functional dependencies. If a parameter value does not vary smoothly with either bias conditions or radiation dose, the data may be suspect.

5.2.4.1.6 Systematic or nonrandom effects. The sampling of lots and parts must be a truly random representation of future lots if valid lot acceptance end-points are to be determined. It pays, therefore, to check whether the data is random in nature. Some typical causes of nonrandom effects are discussed in the sections which follow.

5.2.4.1.6.1 Correlations with respect to time. Lot-to-lot variations should be checked to see if they correlate with time. Examples of such correlations are an average shift with respect to date of manufacture or simply a smooth variation with respect to the date of manufacture. Usually, a look at the data is sufficient to determine if such an effect is occurring. However, more rigorous techniques, such as time-series correlations, for example, exists which can check whether the data varies smoothly with respect to time or has seasonal variations.

5.2.4.1.6.2 Unexpected magnitudes of lot-to-lot variations. If lot-to-lot variations of either the mean value or the standard deviation are much larger or much smaller than expected, it is cause for concern. If a number of lots are very similar, then it may be that the sampling over lots is not truly random. There may be,

for example, a single diffusion lot involved or a single wafer. If the lots were produced under total process control, very small variations may result between lots. Then, if future lots will come from the same process, the characterization data is valid. However, if future lots will not all come from the same process, then the data is not valid.

5.2.4.1.6.3 Other systematic effects. If the data comes from several sources, it can vary systematically, i.e., nonrandomly, according to the source of the data. Even in one test facility, there may be a systematic dependence on test cell, operator, dosimetry equipment, etc. If lots come from several plants, there may be a systematic dependence on which plant supplied the parts. This type of effect should not be common; it is mentioned here to make sure that is not entirely overlooked.

5.2.4.1.6.4 Checking for systematic effects. If data is suspect, it can be checked for self consistency by removing all data having a common attribute such as date, test facility, place of manufacture, operator, etc. If there are no systematic effects, such removal should not seriously perturb the computed results. Likewise, when parameter values or stress to failure are ranked, there should be no grouping by attribute except for lot identity. Another possibility that should be checked is that the devices did not receive some previous radiation of another type. Thus, as an example, ionizing radiation dose data can be obtained from a data bank, but the devices listed may, previously, have been exposed to neutrons.

5.2.4.2 Correcting the data. If the data examination shows that there may be bad data points present then they have to be either corrected or discarded before the data analysis can proceed.

5.2.4.2.1 Correcting bad data. Sometimes an isolated missing, outlying or otherwise faulty measurement may be inferred by interpolation if the parameter varies smoothly with radiation stress or bias. Whether or not data should be corrected is often a matter of judgment. This documentation should identify where inferred data was used to replace incorrect or missing data.

5.2.4.2.2 Discarding bad data. Often, only a single measurement on a device has to be corrected or discarded. However, if one device has many outlying or other obvious measurements, it may be necessary to eliminate the entire series of measurements on that device and seek an explanation of what went wrong. It may be a case of a mismeasurement or of the measuring equipment itself having an effect on the device. On the other hand, the device itself may be an outlier and the question is then raised as to how many outliers will be likely in practice, i.e., when devices are procured for system development and production. If the data shows evidence of many apparent mismeasurements, outlying devices, or outlying lots, then all of the data comes into question. When data is discarded, such action should be documented.

5.2.4.3 Recasting the data to the specified conditions. The assumption is now made that the data examination has been successfully completed and that the data to be analyzed is satisfactory in all respects. One final task now remains before the actual calculation of the end-point limits can be made and that is that the data must be recast into the conditions that will be specified for the lot acceptance tests. Thus, if the lot acceptance test is to be made on a particular parameter, PAR, at a radiation level PHI(SPEC), then the post-radiation values PAR(PHI(SPEC)) must be obtained from the characterization data and they must be obtained for the bias conditions that will also be specified in the procurement document. In general these values will be obtainable by interpolation. In the case of abrupt failure, defined in 5.1.8.7 as a failure level which cannot be determined by interpolation, the mean value and standard deviation of the fluences to abrupt failure in the characterization data should be used to estimate the radiation level at which the part can be safely used.

5.2.4.4 Examples of data analyses. Depending on the exact nature of the data, the statistical methods that should be used to analyze the data and to calculate the required end-point limits range from relatively simple techniques to some that are still under development. Examples are given below for two cases for which the calculations are relatively straightforward. All statistical quantities are assumed to obey lognormal probability distributions i.e., the logarithms of the parameter values are normally distributed. This assumption may be considered reasonable because many of the parameters that are of interest for radiation effects in devices have been observed experimentally to obey a lognormal distribution. In any case, extensions of the analysis techniques discussed below can be made to other types of probability distributions.

5.2.4.4.1 Parameters and delta-parameters. For convenience, the analyses are discussed in terms of the value of the parameter in question after irradiation. In practice, however, it is often useful to measure the changes, or deltas, in a parameter value produced by the irradiation. Again, the extension from the formulas given to the case of parameter deltas is straightforward. It should be noted that lot acceptance tests based on parameter deltas can be somewhat more costly because they require that part identity be maintained and that pre- and post-irradiation parameter values be recorded. They should not be overlooked, however, because, in

d. The characterization data was adequate to provide post-irradiation current gain values, at the required collector current, bias voltage, and temperature at 2.5 x 10^{13} neutrons/cm^2. This data is shown in table XIII. Because this is an illustrative example, data is shown for only ten devices. In actual practice, a sample size of 10 should not be considered adequate to support the calculation of an end-point limit.

For the values in table XIII, the following quantities may be calculated:

MEAN(LN(h_{FE}(PHI(SPEC)))) = 4.591 and

STDEV(LN(h_{FE}(PHI(SPEC)))) = 0.107.

Assumptions b. and c., make C = 0.90 and P = 0.99. The size of the characterization sample is 10. For C = 0.90, P = 0.99, n = 10, the one sided tolerance limit factor, K_{TL}, is found in table XII to be 3.5.32. The end-point limit, RHEPL, is thus:

RHEPL = 4.591 – 3.532 x 0.107 = 4.213

In more familiar terms, the geometric mean value of the current gain for the ten devices in table XII is 98.6, the plus and minus one standard deviation gains are 109.7 and 88.6 respectively, and the end-point limit for the gain is 67.6 (= exp(4.213)). Lot acceptance tests for 2N2222 transistors would then be performed in the future by irradiating 11 devices from each lot to 2.5 x 10^{13} neutrons per cm^2 and requiring that each device out of the 11 have a post irradiation gain greater than 67.6; otherwise the lot is rejected.

TABLE XIII. Post-irradiation data for ten 2N2222 transistors.

PHI(SPEC) = 2.5 x 10^{13} neutrons/cm^2 (1 MeV Si damage equivalent)

Device number	h_{FE}(PHI(SPEC))	LN(h_{FE}(PHI(SPEC)))
1	108.8	4.689
2	105.4	4.657
3	93.7	4.540
4	97.7	4.582
5	102.6	4.630
6	104.5	4.650
7	84.1	4.431
8	101.1	4.616
9	112.5	4.723
10	81.1	4.396

5.2.4.4.5 Case 2. Lot-to-lot variations larger than within lot variations. Case 2 is applicable when within-lot standard deviations are small compared to lot-to-lot variations. In this case, the effective sample size for the RHEPL calculations is the number of lots and not the number of devices used for the characterization measurements. An approximate analysis method for this case was developed by I. Arimura and A. Namenson and published in IEEE Trans. Nucl. Sci., NS-30, 4322, December 1983. The method assumes that the parameters follow a normal or lognormal probability distribution but it can be modified for a different distribution if necessary. Once again the assumption described in 5.2.3.7 is made, namely that the object of the lot acceptance tests is, with 90 percent confidence, to have at least 90 percent of lots pass. It is assumed also that an 11/0 sample size series test will be used for lot acceptance. This last assumption means that, again, the individual part survival probability of the lot being tested for acceptance must be P = 0.99.

5.2.4.4.5.1 Sampling for multi-lot analysis. Ideally, there should be at least five lots with at least five parts in each lot. If the within-lot variations are very small compared to the lot-to-lot variations, the requirement on having at least five parts per lot may be waived.

5.2.4.4.5.2 Steps in multi-lot analysis. The following steps are then used in the calculation:

a. Let the number of lots be N and the number of devices in each lot be n_l. For the Ith lot, calculate the mean value and the standard deviation of the given parameter. Specifically, for the Ith lot, the quantities calculated are $MEAN_l$(PAR (RAD)) and $STDEV_l$(PAR (RAD)) as given by the following equations:

$$MEAN_l\,[PAR\,(RAD)] = \frac{1}{n_l} \sum_{j=1}^{n_l} PAR_{lj}(RAD)$$

where PAR_{lj}(RAD) is the measured value of PAR(RAD) for the jth device in the Ith lot, and

STDEV [PAR (RAD)] =

$$\left[\frac{1}{n_l - 1} \sum_{j=1}^{n_l} [PAR_{lj}(RAD) - MEAN_l\,PAR\,(RAD)]^2\right]^{1/2}$$

b. For each lot multiply the standard deviation by 2.326 (see explanation below) and add it to the mean (addition is used for a parameter that increases in value with increasing radiation level). This gives a limit:

$$LIM_l = MEAN_l(PAR\,(RAD)) + 2.326 \times STDEV_l(PAR\,(RAD)) \quad \text{for the Ith lot.}$$

c. For the N values of LIM_l, obtain the MEAN(LIM) and the standard deviation STDEV(LIM).

d. Look up the one-sided-tolerance-limit factor K_{TL} for 90 percent probability and 90 percent confidence and for a sample size corresponding to N, the number of lots.

e. Use the following equation to obtain the desired RHEPL:

$$RHEPL = MEAN(LIM) + K_{TL}(C = .9, P = .9, N) \times STDEV(LIM)$$

5.2.4.4.5.3 The rationale of the method given above. The rationale of the method given above is to examine the distribution of the 99 percentile points of the different lots and treat them as a normal (or lognormal) distribution. For each lot, adding MEAN(PAR) + 2.326 x STDEV(PAR) gives the best estimate of the 99 percentile point because, for a standard normal distribution, 2.326 standard deviations above the mean includes 99 percent of the distribution. The K_{TL} factor in step D above then is used to obtain an estimate that, with 90 percent confidence, 90 percent of the lots will have 99 percent of their parts within the calculated RHEPL.

5.2.4.4.5.4 An illustrative example of an RHEPL calculation for case 2. The following example was taken from actual data on voltage shifts (deltas) measured after an ionizing radiation dose of 400 kRad. (This data is interesting for other reasons as well and, for those reasons, will be discussed in greater detail in appendix II.) The lots do not all have five parts per lot, but the within-lot standard deviations are so small compared to the lot-to-lot variations that the case 2 method can still be used. The data in this example is treated as a normal distribution (instead of a lognormal distribution).

The values shown in table XIV yield the values shown in table XVI.

APPENDIX A

A LISTING OF CORRESPONDING ERRIC AND MILTARY STANDARD SYMBOLS

10. SCOPE

10.1 Scope. This appendix is to establish a correlation between ERRIC symbols and military standard symbols. This appendix is not a mandatory part of the handbook. The information contained herein is intended for guidance only.

20. APPLICABLE DOCUMENTS. This section is not applicable to this appendix.

30. A LISTING OF CORRESPONDING ERRIC AND MILITARY STANDARD SYMBOLS

Item	ERRIC symbol	Military Standard symbol
Currents		
High level input current	IIH	I_{IH}
Low level input current	IIL	I_{IL}
Output short circuit current	IOS	I_{OS}
High level supply current	ICC	I_{CCH}
Low level supply current	ICC	I_{CCL}
Emitter-base cutoff current	IEBO	I_{EBO}
Collector-base cutoff current	ICBO	I_{CBO}
Current flow into an input terminal	IIN	I_{IN}
Input offset current	OFSTI	I_{IO}
Input bias current	IBIAS	I_{IB}
Zero scale current	IZS	I_{ZS}
Full scale current	IFS	I_{FS}
Impedances		
Resistance	R	R
Input resistance	RI	
Output impedance	ZOUT	Z_O
Output resistance	ROUT	
On resistance	RON	
On resistance	RDS	R_{DS}
Time		
High-low propagation delay time	TPHL	t_{PHL}
Low-high propagation delay time	TPLH	t_{PLH}

Reverse recovery time	TRR	t_{RR}
Rise time	TR	t_{TLH}
Fall time	TF	t_{THL}

Rejection ratios

Common mode rejection ratio	CM RR	CM_{rr}
Positive power supply rejection ratio	PWSRRP	+PSRR
		PS_{rr}
Negative power supply rejection ratio	PWSRRN	-PSRR
		PS_{rr}

Gains and transfer ratios

Forward current transfer ratio	HFE	h_{FE}
Power gain	AP	P_G
Maximum automatic gain control range	MAGC	A_{GC}

Other

Noise figure	NF	N_F
Slew rate	SL RA	S_R
Nonlinearity	NL	N_L
Power supply sensitivity	PSSIFS	$P_{SS}I_{FS}$
Bit error	BERR	SIGMA-NL

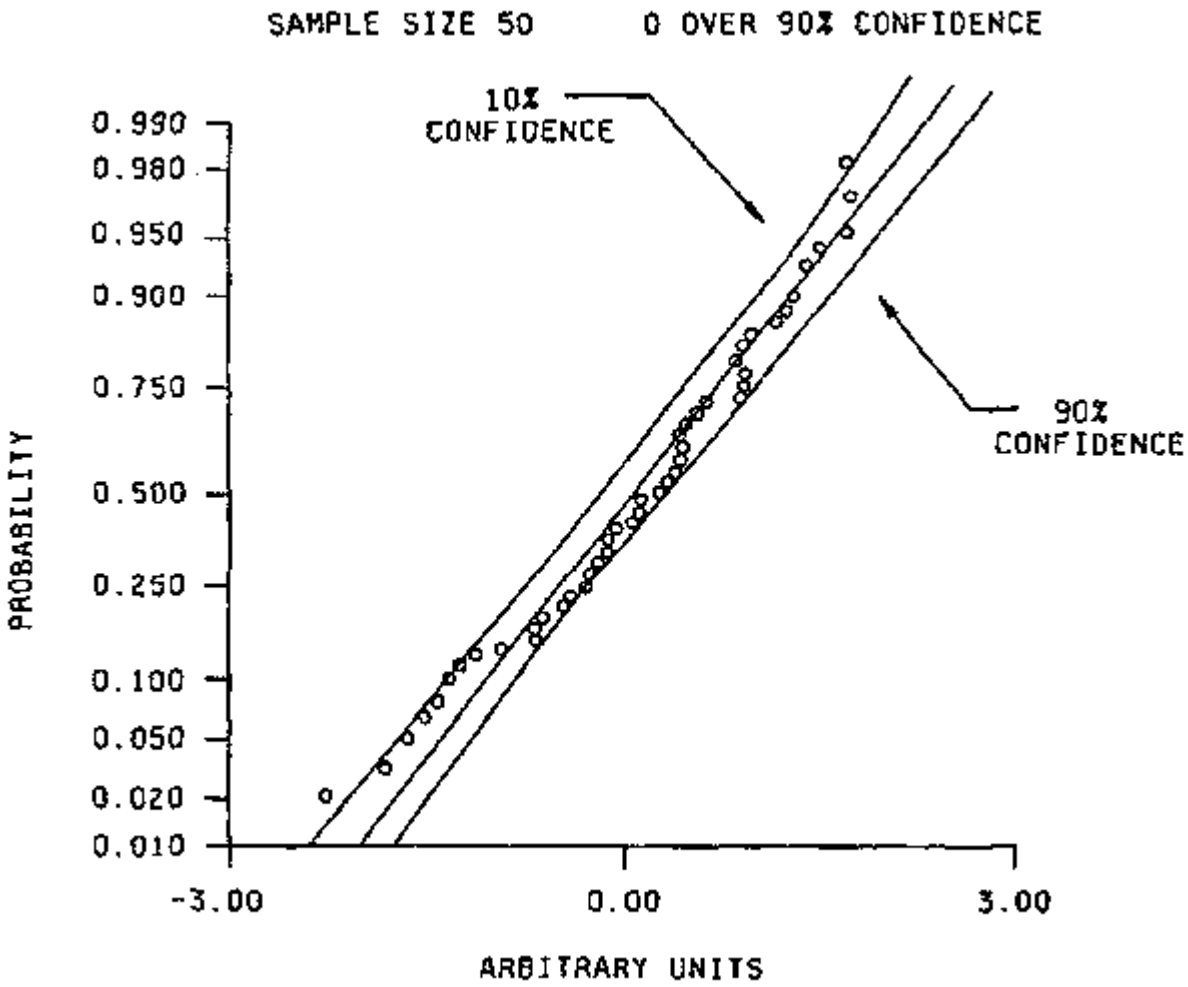

FIGURE 10. Normal probability plot of 50 points with an exceptionally bad fit - simulated data.

60.3.1.1 Example of inhomogeneous data. Figure 11 shows the resulting cumulative probability plot on normal probability paper with the 90 percent and 10 percent confidence lines. It is clearly not a typical normal distribution. A goodness of fit test (to be discussed later) indicates only a 0.1 percent confidence that this data could result from a true normal distribution.

APPENDIX B

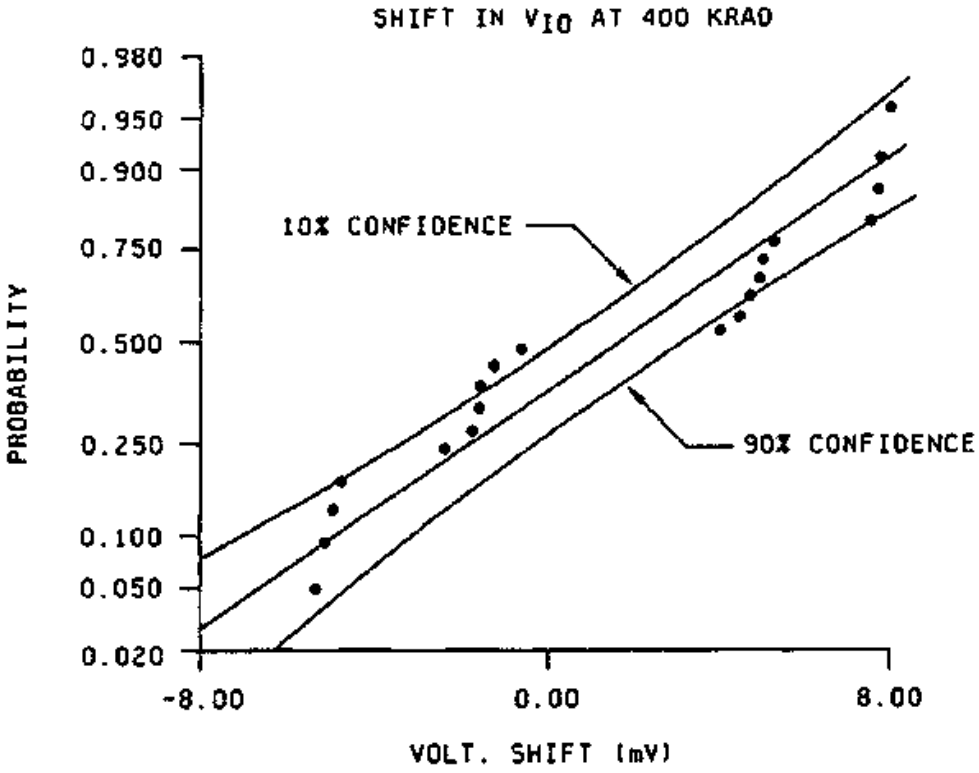

FIGURE 11. Normal probability plot of actual data that exhibited systematic effects.

60.3.1.1.1 Seeking the causes of inhomogeneity in the example. A study of the plot shows that the ICs must have come from two distinct batches (one batch being ICs R1, R3, R5 and the other being R2, R4). In addition, the response of the circuits varies systematically according to which side of the die the circuit was found (one side being circuits C1 and C2 and the other being C3 and C4). Thus, any circuit belongs to one of four groups as illustrated on figure 12. This figure is the plot of figure 11 without confidence lines but with the points “colored” to show how each group corresponds to a unique set of attributes. Systematic effects are present, this is an inhomogeneous lot and sample size corrections (see 70.3 and DNA documents referenced in 2.2.1) indicate an effective sample size of six which is not in statistical disagreement with the fact that the data separates into four distinct groups. Any treatment of this data should use an effective sample size between four and six and not estimate probabilities greater than about 84 percent. If the system survivability were to be calculated, the specific buy of parts (how many batches) would be relevant information. Often it is not possible to find a set of attributes which fit some obvious clumping of points. Nevertheless, it would remain very likely that systematics are a serious perturbation and sample size corrections would be appropriate as well as estimates of a maximum reliable survival probability which could be estimated from that effective sample size.

APPENDIX B

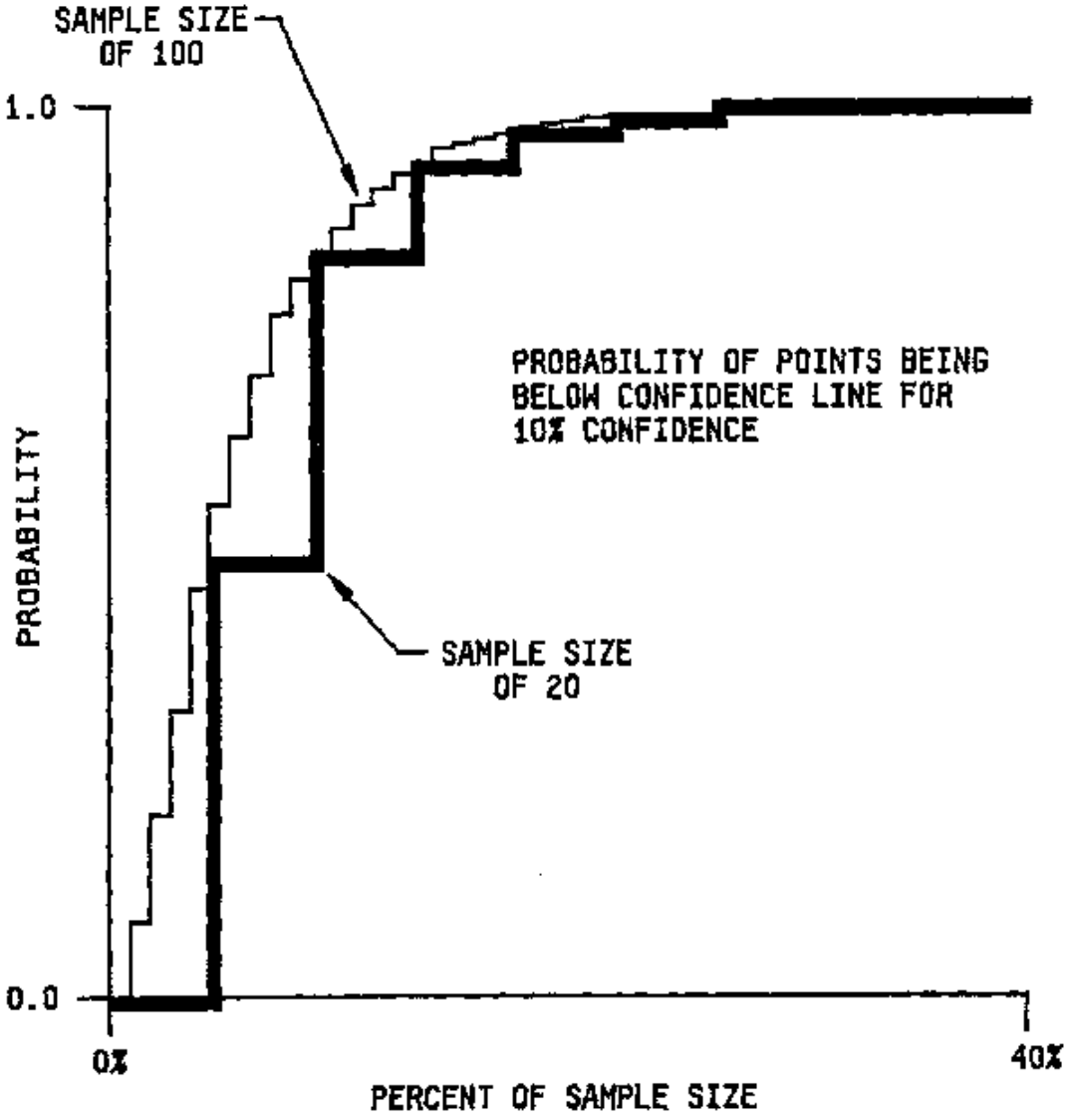

FIGURE 17. Expected fraction of devices which exceed 10 percent confidence line. Sample sizes of 20 and 100.

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Custodians:
Army - CR
Navy - EC
Air Force - 19
DLA - CC

Review activities:
Army – AR, MI, SM
Navy – AS, CG, MC, OS, SH
Air Force – 11, 99
NASA – NA
DTRA - TDAR

Preparing activity:
DLA – CC

(Project 59GP-0114)

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