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MILITARY HANDBOOK

NEUTRON HARDNESS ASSURANCE GUIDELINES FOR SEMICONDUCTOR DEVICES AND MICROCIRCUITS

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Neutron Hardness Assurance Guidelines for Semiconductor Devices and Microcircuits

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

2. This publication was approved 29 January 1985 for printing and inclusion in the military standardization handbook series.

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

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

FOREWORD

The purpose of this handbook is to provide guidelines of a systematic approach to the selection and procurement of electronic piece parts, which shall be used in a system that must survive in a specified neutron environment.

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1. SCOPE

Hardness assurance (HA) for electronic piece parts is the application of methods and procedures during the procurement of an electronic piece part to ensure that the radiation response of the purchased part is within known and acceptable limits. The scope of this handbook is limited to hardness assurance with respect to neutron radiation effects on piece-part semiconductor devices and microcircuits. An assumption underlying the handbook is that the neutron environment which the system must survive is specified.

1.1 Objectives. Systems which must operate in a nuclear environment must be capable of nuclear survivability, which means that they shall be able to complete their mission in spite of nuclear radiation induced stresses. Radiation hardening of a system is the process of making sure that a system is designed to survive a specific set of nuclear threats. Hardness assurance (HA) is the application of methods and procedures during production of a system to make certain that it is produced with the hardness level that was designed into it. Although HA is performed during the production phases of a system, experiences has shown that it must be considered during the design phases if a cost effective system is to be obtained.

An important goal of this handbook is to promote the standardization of hardness assurance procedures, so that the benefits of standardizaton such as, for example, reduced requirements for documentaton and for contractual negotiations, can be realized for radiation hardened systems.

This handbook has been written for those who carry out the HA functions but it will also be a valuable guide for the designers of radiation hardened systems who develop the hardness assurance design documentation (HADD). The designers must keep the costs of HA in mind as they design the system. The HA personnel must on the other hand utilize the requirements and documentation established during design in order to carry out the HA activities. Any HA requirements not provided during the design hardening phase must be determined by the HA personnel on the basis of the design guidelines defined in Paragraph 5.1.

1.2 Handbook application. The subject of system hardness assurance is sufficiently complex and dependent upon the details of system mission requirements, time schedules, and costs that substantial standardization of system hardness assurance procedures is clearly a much more difficult problem than it is for piece parts hardness assurance. For this reason this handbook mainly discusses piece part hardness assurance methods and discusses system hardness assurance topics only as they are necessary to complete the discussion for piece parts. Thus the discussion will deal in detail with methods for characterizing the radiation responses of parts and for categorizing them according to certain criteria which will determine how stringently controls will need to be applied during part procurement. Specific activities and functions which may be significantly different for different systems and for different contracting organizations will not be discussed in detail.

1.3 Effects beyond the scope of the handbook - reliability budget considerations. Neutron effects are rarely the only consideration for system survivability. Additional effects such as aging, other nuclear radiation effects (for example, total ionizing dose, electromagnetic pulse (EMP), etc.) and other environmental effects (for example, temperature) can also cause system failure. These additional effects impact on the neutron requirements since they often determine how stringent the neutron requirements must be. For example, a part which is highly likely to fail due to temperature variations may require an extra low failure probability from becoming too large. On the other hand, if the part is insensitive to temperature variations, a higher failure probability specifically due to the neutron damage mechanisms may be tolerated. The problem of assigning acceptable risks to other failure mechanisms (reliability budget considerations), and their impact on the neutron hardening considerations are beyond the scope of this document. However, more information and an example of system failure budget considerations may be found in reference 1.

2. REFERENCED DOCUMENTS

2.1 Government documents.

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

SPECIFICATIONS

MILITARY

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

STANDARDS

MILITARY

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

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

3. DEFINITIONS

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

3.1.1 Confidence level. (C) is the probability (usually given in percent) that at least a proportion, P_{DIST}, of the parts in the lot will survive. See paragraph 50.3 in Appendix E.

3.1.2 Cumulative probability. (P_{DIST}) is the percentage or proportion of a probability distribution which is below a given upper limit (or above a given lower limit). P_{DIST} thus corresponds to the probability that a parameter is below a given uppper limit (or above a given lower limit). See paragraph 50.1.2.2 in Appendix E.

3.1.3 Design margin break point (DMBP). A single categorization criterion which applies to all (or almost all) parts in a system. The NDM of parts is compared to DMBP to determine part categories. See paragraphs 5.1.1.1 and 5.1.6.1.

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

3.1.5 Lot acceptance test. Is the testing of a sample of parts from a procurement lot to determine if the lot is acceptable. It is intended to be a generic term so as to standardize on such commonly used expressions as Lot Conformance Test and Quality Conformance Test. In these guidelines, lot acceptance tests refer to tests performed with nuclear radiation.

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

3.1.7 Mean fluence-to-failure value. (ϕ_{MF}) $\phi_{MF} = e^{\overline{\ln(\phi_{FAIL})}}$

3.1.8 Measured logarithmic mean for PAR_{RAD}. ($\overline{\ln(PAR_{RAD})}$)

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

$\overline{\ln(PAR_{RAD})}$ is useful for lognormally distributed variables. See paragraph 50.2.2.1 in Appendix E.

3.1.9 Measured logarithmic mean for ϕ_{FAIL}. ($\overline{\ln(\phi_{FAIL})}$)

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

3.1.10 Measured logarithmic standard deviation for ϕ_{FAIL}. ($S_{ln}(\phi_{FAIL})$)

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

3.1.11 Measured Logarithmic standard deviation for PAR_{RAD}. ($S_{ln}(PAR_{RAD})$)

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

3.1.12 Measured mean for PAR. ($\overline{PAR}$)

$$\overline{PAR} \equiv \frac{1}{n} \sum_{i-1}^{n} PAR_i$$

where Par_i is the parameter value measured for the ith device.

3.1.13 Measured standard deviation for PAR. (S (PAR_{RAD})).

$$s(PAR_{RAD}) \equiv \left\{ \frac{1}{(n-1)} \sum_{i=1}^{n} \left(PAR_{RAD_i} - (\overline{PAR} \right)^2 \right\}^{1/2}$$

3.1.14 Neutron design margin. (NDM) NDM = ϕ_{MF}/ϕ_{SPEC}.

3.1.15 Neutron-fluence. (ϕ) is the neutron fluence value under consideration. It is often stated in terms of a 1 MeV(Si) equivalent fluence.

3.1.16 Neutron fluence to failure value. (ϕ_{FAIL}) is the neutron fluence value for the part under test, at which PAR_{RAD} equals PAR_{FAIL}.

3.1.17 One sided tolerance limit. (K_{TL}). If n values of parameter PAR are measured, and PAR is normally distributed, then with confidence C, there is at least a probability P_{DIST} that the parameter in the parent population is less than

$$\overline{PAR} + K_{TL}(n,C,P_{DIST})S(PAR)$$

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

$$\overline{PAR} - K_{TL}(n,C,P_{DIST})S(PAR)$$

(for situations where PAR must not exceed a lower limit PAR_{MIN}). A more detailed discussion of how one-sided tolerace limits are used in sampling statistics is given in paragraph 50.3.2 of Appendix E.

3.1.18 Parameter design margin. (DM)

$$DM = PAR_{FAIL} / e^{\overline{In(PAR_{RAD})}}$$

for increasing parameter values, and

$$DM = e^{\overline{In(PAR_{RAD})}} / PAR_{FAIL}$$

for decreasing parameter values.

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

3.1.20 Parameter specification value. (PAR_{MIN} or PAR_{MAX}) is the specified minimum or maximum device parameter value prior to irradiation. This value is usually given by the manufacturer.

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

3.1.22 Part categorizaton criterion (PCC). A categorization criterion which applies to only one part type in a system. The NDM of a part type is compared to its PCC to determine its part category. See paragraph 5.1.1.1 and 5.1.6.2.

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

3.1.24 Radiation-induced parameter value. (PAR_{RAD}) is the post-irradiation parameter value.

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

3.1.26 Specified neutron fluence. - (ϕ_{SPEC}) is the maximum neutron fluence which the circuit under consideration must survive.

3.2 Symbols. (see definitions).

C	Confidence level
DM	Parameter design margin
DMBP	Design Margin Break Point
K_{TL}	One-sided tolerance limit factor
$\overline{\ln(PAR_{RAD})}$	Measured logarithmic mean for PAR_{RAD}
$\overline{\ln(\phi_{FAIL})}$	Measured logarithmic mean for ϕ_{FAIL}
n	Sample size
N	Lot size
NDM	Neutron design margin
PAR	Device parameter value
PAR_{FAIL}	Parameter failure value
PAR_{MIN} or PAR_{MAX}	Specified parameter value (minimum or maximum)
PAR_{RAD}	Radiation-induced parameter value
PCC	Part categorization criterion
P_{DIST}	Cumulative proportion of distribution
$S_{\ln(PAR_{RAD})}$	Measured logarithmic standard deviation for PAR_{RAD}
$S_{\ln(\phi_{FAIL})}$	Measured logarithmic standard deviation for ϕ_{FAIL}
ϕ_{FAIL}	Neutron fluence-to-failure value
ϕ_{MF}	Mean neutron fluence-to failure
ϕ_{SPEC}	Specified neutron fluence

3.3 Abbreviations.

CCB	Configuration Control Board. (See paragraph 4.4.1)
HA	Hardness Assurance. (See paragraph 1.1.)
HADD	Hardness Assurance Design Documentation. (See paragraph 4.4.2)

HM	Hardness Maintenance. (See paragraph 4.3).
HCI	Hardness Critical Item. (See paragraph 4.4.2.).
PMO	Project Manager's Office. The PMO is the overall controlling organization for the project under consideration. It is intended to be a generic term so as to standardize, for the purposes of this handbook, such expressions as System, System Project, Project Manager's Office, Project Manager, Procurement Agency, and Contracting Agency.
T.O.	Technical Orders. (See paragraph 4.4.2.).

4. GENERAL NEUTRON HARDNESS ASSURANCE REQUIREMENTS

Hardness assurance requirements involve a knowledge of radiation design hardening as well as a knowledge of the specific devices which will be used in a particular circuit. The main text deals with those aspects of design hardening and hardness assurance which generally apply to all devices. These general procedues will be clarified with examples using specific devices. However, details for specific part types, such as test procedures and statistical analysis techniques, will be left for the appendices. This approach has been adopted so that the text could present a clear overall view of hardness assurance techniques free of unnecessary details. It is also convenient because the main text should not be subject to major revisions while the appendices can be updated in the fugure as more information and experience are obtained.

4.1 Overview of radiation design hardening. Radiation design hardening is a process in which circuit design, parts selection, and hardness assessment are performed to achieve an optimum and cost effective hardened circuit design. In cases where the system specifications are difficult to satisfy, these steps in design hardening may have to be iterated until a satisfactory design and selection of parts is achieved.

During circuit design hardening, candidate device types are evaluated quantitatively for their neutron hardness and radiation testing is performed for this purpose if insufficient information exists about the radiation response of the devices. On the basis of such an evaluation, each part type is categorized according to one of the following categories:

Unacceptable Parts: All parts with such small design margins that the cost of hardness assurance testing is judged to be prohibitive. See paragraph 5.1.2.4.1.

HCC-1 Parts: All parts which require special checking or special testing for HA purposes are classified as HCC-1 parts. See paragraph 5.1.2.1.

HCC-2 Parts: HCC-2 parts are those which exceed radiation requirements by such large margins that no special testing is required on a routine basis.

Some occasional testing may be required to verify that the manufacturing processes have not changed significantly and that the part still belongs to HCC-2. See paragraph 5.1.2.2.

Hardness non-critical parts: Hardness non-critical (HNC) parts are those parts which have such large design margins that they do not require testing even on an occasional basis. (See paragraph 5.1.2.3.)

4.2 Overview of radiation hardness assurance. Hardness assurance for electronic piece parts is the applicaiton of methods and procedures during the procurement of an electronic piece part to ensure that the radiation response of the purchased part is within known and acceptable limits. Hardness assurance for piece parts takes place during the system production and part procurement phases. The tests and the screens which were determined during the design phase and described in detail in the HADD are put into effect during the hardness assurance phase. Paragraph 5.2 will deal in greater detail with hardness assurance for piece part procurement.

4.3 Overview of radiation hardness maintenance. Nuclear radiation hardness maintenance (HM) consists of those activities which insure that the system remains hard after it has been produced. It may include part reprocurement and tests and screens similar to those applied during the system production phase. It will also include checks to assure that the piece-part manufacturing processes have not changed in such a way as to affect the response of the parts to neutron radiation adversely. Such checks may require periodic information to be furnished by the manufacturer, and/or periodic tests as mentioned above. It may occur during systems hardness maintenance that the piece part type called for in the original design is no longer in manufacture. In such case, a substitute part type will have to be selected, characterized, and qualified in the same way as was done for the original part.

No special section is devoted to system radiation hardness maintenance since the piece part related activities performed at the time are generally the same as those performed during radiation design hardening and system production.

4.4 Piece-part hardness assurance considerations which will not be considered in detail. General guidelines for piece-part HA activities cannot be given whenever the details of such activities are highly dependent on consideration specific to the particular system or to the structure of the particular contracting organizations. Such activities are, nevertheless, a necessary part of HA, and the contracting organizations must have detailed plans for carrying them out. Some of these activities are discussed in the two sections which follow.

4.4.1 Parts and configuration control. In order to assure that the system is produced and maintained with the hardness of the original design, controls will be required both on the piece parts and on the system configuration. Piece part control is usually performed by a parts control board (PCB) whose responsibility it is to make sure that inferior parts are not substituted for the original piece part types used in the hardened design. In general, the selection and qualificaton of piece parts and the development of piece part procurement specifications will take place during the design hardening and test phase of the system. Actual piece part procurements will then be made during system production and, during system maintenance when replacement parts are required. Configuration control, which will include such factors as circuit design, layout, and locaton within the system, is usually performed by a configuration control board (CCB)) whose responsibility it is to see that circuit designs, layouts etc., are not changed in such a way as to reduce the hardness of the original design. The configuration control board will also institute checks to make sure that piece parts identified as critical to the hardness of a circuit are not inadvertently left out during assembly. Parts-control and configuration control boards are active during the three main phases of system development, namely: design hardening and test, production, and hardness maintenance.

4.4.2 Hardness assurance design documentaion. It will often be the case that the three phases mentioned in the last paragraph are separated in time by periods which can be as long as a few years, and that they may be performed by entirely separate government agencies and contractors. A critical task during the system design hardening phase, therefore, is the preparation of hardness assurance design documentation (HADD) which can be transmitted from the design phase and the initial performing organizations, to the performing organizations associated with the production and hardness maintenance phases. Only hardness critical items (HCI) or mission-critical components are subject to hardening requirements and, therefore, only these components should be subject to HADD requirements.

Much of the information required for the HA program will be available in other program documentation such as Technical Orders (TO's), Verification Reports, Part Specifications, and Failure Analysis Reports. This documented information generally will be incorporated into the HADD by reference and copies of these reports should be maintained as a part of the HADD. Data required but not available in these sources must be documented for inclusion in the HADD. Additional information on HADD may be obtained from documents such as references 2 and 3.

5. DETAILED NEUTRON HARDNESS ASSURANCE REQUIREMENTS

5.1 Radiation design hardening. This section discusses the system nuclear radiation design hardening activities which are basic to a hardness assurance (HA) program. These activities take place prior to system production. Design hardening, part selection, and the part categorization criteria developed during the system design are instrumental in establishing the cost of the HA and HM activities required throughout the life of the system. A major goal in design, therefore, is to select parts and circuit design so as to minimize the degreee of controls, screens, and costly testing that will be required in the future. It will generally prove most economical over the life of a system if the need for future testing is eliminated by carefully selecting radiation hard parts, even if they are more expensive, or by hardening a circuit, even if the circuit complexity is thereby increased. This section provides guidelines for establishing HA requirements during system design and hardening.

Although these guidelines provide the necessary steps for developing a HA program, it is highly desirable that additional detailed guidance be obtained from a parts radiation effects specialist as early in the design stages of the HA program as practicable. Such a specialist can be helpful in providing current radiation effects information regarding parts application and selection and as a consultant for the many special problems that may develop during the design phases of a program.

The steps to be followed in the design hardening activities are listed below along with the paragraph numbers in which more detailed discussions of each item may be found.

a. Part selection and circuit hardening techniques. (paragraph 5.1.2)

b. Determination of the circuit parameter failure value, PAR_{FAIL} for each part application on the basis of a worst case circuit analysis. (paragraph 5.1.3)

c. Determination of the mean neutron failure fluence, ϕ_{MF}, using PAR_{FAIL} and the characterization data for the part under evaluation. (paragraph 5.1.4)

d. Calculation of the neutron design margin, NDM, as the ratio of ϕ_{MF} for each part type to the specified neutron fluence ϕ_{SPEC} that the system must survive. Alternatively, in some cases it may be better to use a parameter design margin, DM(PAR), which compares the mean value of a critical parameter, $PAR_{(MEAN)} = \exp \ln(PAR_{RAD})$, at the fluence ϕ_{SPEC} to the value $PAR_{(FAIL)}$ which will cause a circuit to fail. (paragraphs 5.1.5 and 5.1.6)

e. Determination of part categorizaton criteria, PCC. Neutron design margins for the various part types are compared to the corresponding categorization criteria to determine the amount of future testing which will be required (paragraph 5.1.6.1). (In the Design Margin Break Point Method a single criterion is applied to all part types. See paragraphs 5.1.1.1 and 5.1.6.1)

f. Categorization of the part, for the application being evaluated, as hardness critical category-1 (lot acceptance testing, screening, or special labeling of parts required), hardness critical category-2 (characterization testing required only occasionally), or hardness non-critical (no testing required). The use of as many hardness non-critical and hardness critical category-2 parts as possible is desirable because it minimizes costly lot acceptance testing and/or screening both during system production and subsequently, during system hardness maintenance. Noncritical parts result in an added saving since they do not have to be documented in the HADD. After characterization measurements have been performed, some part types may be found to have design margins which are so low that they should be classified as unacceptable and eliminated from further consideration (see paragraph 5.1.2.4.1).

5.1.1 System considerations and part categorization methods.

5.1.1.1 The design margin break point (DMBP) method and the part categorization criteria (PCC) method. Two different part categorization methods may be considered during the design hardening phase of a system. Both methods are ultimately based on statistical analysis.

The first method, called the Design Margin Break Point (DMBP) method, applies a single categorization criterion to all parts in the system. This method is generally most practical for systems with moderate requirements. It assumes that the moderate system requirements are easily attainable even under worst case assumptions about the most neutron sensitive parts of the system. In such cases, there is no point, therefore, in examining each part type separately. This method has been used by the U.S Air Force (references 2 and 3a) and by the U.S. Army (reference 3b).

The second method is called the Part Categorization Criteria (PCC) method (references 4 and 5) and is applied to systems with more stringent requirements (for example high neutron fluences and/or high survival probabilities). Because the application of worst case assumptions to all the parts in the system would be far too conservative, the PCC method applies a separate categorization criterion to each individual part type. This method, is based on techniques widely used in industrial quality control (reference 6).

Detailed discussions of these two methods and of the impact each has on hardness assurance will be given in paragraph 5.1.6 which discusses part categorization criteria. However, some introductory remarks and a comparison of the two methods will be useful here.

a. The DMBP method has the advantage of applying a single simple rule to all parts in the system and, therefore, greatly simplifies the HADD documentation.

b. The DMBP method has the disadvantage of leading to large overdesigns and may result in an unnecessarily large number of parts being put in HCC-1.

c. The PCC approach has the advantage of leading to lower part categorization criteria and, therefore, more HCC-2 parts (only occasional testing). This approach can therefore reduce costs over the life cycle of the system.

d. The PCC approach has the disadvantage of complicating the HADD documentation because each part type can have a different part categorization criterion.

The choice of which approach to use is based on engineering judgement, system costs, schedules, and other factors specific to the system.

In some systems it may be that the DMBP method will apply to almost all the parts in the system and that only a few part types will require special attention. For such systems, a single categorization criterion (the DMBP method) will be applied to all part types except those that require special attention. Application of the mixed method makes the piece part analyses and the HADD documentation simpler than they would be if only the PCC method were used and all the parts required special attention.

Systems with very stringent requirements may necessitate a detailed analysis of the circuitry and of the failure probability of the whole system and may even include Monte-Carlo calculations. Such analyses are beyond the scope of this document. If they are required, quality control and radiation effects specialists should be consulted.

5.1.2. Categorization and selection of parts. Some mention has already been made of hardness critical part categories 1 and 2 and of hardness non-critical parts. These categories, determine during the design phase of a system, play an important role during the HA phase when parts are procured. More attention will be given to part categorizaion in the paragraph on categorization criteria (paragraph 5.1.6). In the present section, the categories will be defined and some general information will be given on the role of categories in part selection.

5.1.2.1 Hardness critical category-1 parts. All parts which require special checking or special testing for HA purposes are classified as HCC-1 parts. Because it may be possible to replace and sometimes eliminate such parts without affecting the operation of the circuit when it is tested in the absence of radiation, it is necessary to assure that

a. parts which require radiation testing or electronic screening have actually been tested or screened,

b. no substitutions are made, and

c. hardness dedicated parts have actually been placed in the circuit.

HCC-1 parts may be subdivided into HCC-1H parts, HCC-1M parts, and HCC-1S parts.

5.1.2.1.1 HCC-1H parts. HCC-1H parts are those which are sufficiently hard to radiation, but which nevertheless, require special attention because they are hardness dedicated (as for example, a clamping diode). The only function of the part is to harden a circuit and under non-radiation conditions the circuit would function without it. Therefore, it is necessary to check only for the presence of the part in the circuit. Experience has shown that identifying HCC-1H parts is necessary in the HADD in order to assure that such parts will remain in the design throughout the life cycle of the system.

5.1.2.1.2 HCC-1M parts. HCC-1M parts are of marginal hardness. Therefore, either:

a. each time a lot is purchased, a sample from that lot must be tested for its response to radiation and analyzed to assure that the part survival probability will be within acceptable limits, or

b. an electrical screen or other special requirement is necessary for radiation hardness assurance purposes.

Electrical screens are usually preferable to radiation testing since they are less costly and easier to implement. Examples of such screens are screens on the gain of a transistor (higher initial gains yield higher post-irradiation gains) or on f_T (because this parameter is correlated with resistance to neutron damage).

If a part is categorized as HCC-1M, consideration should be given to additional circuit design hardening to make the part HCC-2 or to replace radiation testing with electrical screens.

5.1.2.1.3 HCC-1S parts. HCC-1S parts are parts which require no routine radiation testing or elctrical screening provided special controls are imposed during the manufacture of these parts. Usually these controls will specify a sole source manufacturer. Some occasional testing of these parts may be required to assure that the selected manufacturer's process has not changed.

5.1.2.1.4 Hierarchy of HCC-1 parts. Some HCC-1 parts may require more than one of the above mentioned controls. A hierarchy is established to remove possible ambiguity in part classificaton. In descending order the hierarchy is:

HCC-1M

HCC-1S

HCC-1H

A part in any level in the hierarchy may require any of the conditions imposed on parts in a lower level. For example, a hardness dedicated part which must be bought from a sole source manufacturer is a HCC-1S part. A part which requires a sole source manufacturer and also lot acceptance testing is a HCC-1M part.

5.1.2.2 HCC-2 parts. HCC-2 parts are those which exceed radiation requirements by such large margins that no special testing is required on a routine basis. Some occasional testing may be required to verify that the manufacturing processes have not changed significantly and that the part still belongs in HCC-2. This would be true if there were a long period of time such as, for example, a year between the characterization tests and part procurement. Often, there will exist a sufficient amount of radiation data on some parts (for example, bipolar silicon transistors) so that a part may be characterized as HCC-2 through the analysis of such data. HCC-2 parts must have quality control provisions equal to or greater than MIL-S-19500, JANTX or MIL-M-38510, Class B.

5.1.2.2.1 HCC-2 parts - radiation specifications below $10^{12} n/cm^2$. For low levels of radiation, some part types may be classified as HCC-2 without radiation testing.

For $\phi_{SPEC} \leq 10^{12} n/cm^2$ (1-MeV Silicon euqivalent) the following semiconductor parts, except for high precision applications, can be considered as Category-2 parts:

Single junction diodes,
High frequency transistors (f_T greater than 50 MHz),
DTL,
ECL,
TTL,
Schottky TTL,
MOS devices (but excluding NMOS),

5.1.2.3 Hardness non-critical parts. Hardness non-critical parts are those parts which have such large design margins that they require no testing even on an occasional basis.

5.1.2.3.1 Hardness non-critical parts-radiation specifications below $10^{12} n/cm^2$. When ϕ_{SPEC} does not exceed $10^{12} n/cm^2$ (1-MeV silicon equivalent), the following non-semiconductor part types can be considered hardness non-critical with the exception of special extreme precision, circuit applications:

Inductors,
Capacitors,
Resistors,
Magnetic devices,
Electro-mechanical devices (provided they do not contain solid state devices).

5.1.2.3.2 Hardness non-critical parts-radiation specifications below $10^{11} n/cm^2$. Because neutron damage mechanisms in silicon bipolar transistors are well understood, it is possible on the basis of a worst case transistor model, to calculate that for neutron fluences of $10^{11} n/cm^2$ (1 MeV silicon euqivalent) or below, silicon transistors (with f_T greater than $5MH_z$) and ICs will not suffer any significant degradation of performance (See Appendix A). For ϕ_{SPEC} less than $10^{11} n/cm^2$, therefore, all silicon bipolar devices, with the possible exception of special devices and those used in special or extreme precision applications may be considered to be hardness non-critical parts.

5.1.2.4 Parts selection. During design hardening, one of the most effective steps for reducing hardness assurance costs is the proper selection of radiation resistant parts. Because radiation lot acceptance testing is relatively expensive, the accumulated costs of such testing over the life cycle of the system, as has already been mentioned, may be quite high. Clearly, it is most desirable to find as many parts as possible which will qualify as non-critical or else as HCC-2 since this procedure avoids routine future lot aceptance testing.

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

a. Part types with design margins less than one will not be used.

b. Part types with design margins between one and two should only be used if no alternatives are available. On the basis of calculations for silicon bipolar transistors, a high rate of lot rejection and/or part failure is to be expected when parts with design margins less than two are used.

The HADD, of course, will not contain an unacceptable part category since it only lists parts which can be used in the system.

5.1.3 Circuit design and analysis. Like part selection, circuit hardening can be a very effective way of reducing HA costs. Again, if a circuit can be redesigned to change the classification of a part either from HCC-2 to non critical, or from HCC-1 to HCC-2, then such redesign may be highly cost effective over the life cycle of the system. Although the subject is very complex and a complete treatment is beyond the scope of this handbook, the following suggestions may be mentioned:

a. Where practicable, circuits should be designed so as to maximize the use of non-radiation sensitive parts.

b. Circuits should be designed so as to minimize the sensitivity of critical parameters, i.e. transistors should be operated at the collector current that maximizes gain margin, and the output drive current should have an adequate design margin after irradiation.

c. Circuits should be designed with large design margins to accomodate changes in sensitive parameters such as current gain.

5.1.3.1 Worst case circuits analysis. A worst case circuit analysis of each circuit in the system is required in order to determine PAR_{FAIL} for a particular piece part type and to evaluate the systems's susceptibility to the radiation environment. Worst-case circuit analysis requires a knowledge of

a. the device types to be used,

b. the radiation sensitive parameters, and

c. the circuit requirements, including, temperature derating and aging.

If necessary, the worst case circuit analysis should take into account the radiation degradation, at one times ϕ_{SPEC}, of any electronic parts or circuits which interact with the one in question. (For example, a power supply voltage may drop because of radiation.) In such a case, the worst case circuit analysis will have to be an iterative procedure. The exact circuit analysis and method of accounting for radiation degradation will be specific to the systems and circuits in question and, therefore, beyond the scope of a piece-parts handbook such as this. In addition, parameters such as frequency, bias, temperature and so forth may also enter into the equations. With these inputs, an end point electrical parameter failure value, PAR_{FAIL}, is determined which is known as the circuit failure value for the device parameter in question. Whether PAR_{FAIL} is an upper limit or a lower limit must be noted when the value of PAR_{FAIL} is given.

5.1.3.2 Use of ΔPAR as a critical parameter. After the value of PAR_{FAIL} has been determined from the worst-case circuit analysis, it is used to determine the neutron failure fluence, ϕ_{FAIL}, as described in paragraph 5.1.4. For each sensitive device type there is usually only one electrical parameter that is of primary interest. This parameter therefore makes up the bulk of the data available in radiation effects data banks. In addition to this primary parameter, other parameters could be critical for special or unusual device applications. These special parameters may or may not be intrinsically sensitive to radiation, and each case must be evaluated individually. This subject is further discussed in the Appendices.

In some cases the condition for proper circuit operation will be that the change in a parameter - ΔPAR - must not exceed a certain value. In this case the critical failure limit is $(\Delta PAR)_{FAIL}$. Often this condition is imposed to give an added margin of safety, or because there is a theoretical predicton for ΔPAR, or for both these reasons. A good illustration is the case of silicon bipolar transistors where it is known that the change in reciprocal current gain is proportional to neutron fluence:

$$\Delta(1/h_{FE}) \propto \phi$$

In such a case the critical failure limit is

$$\Delta(1/h_{FE})_{FAIL} = 1/h_{FE(FAIL)} - 1/h_{FE(MIN)}$$

where $h_{FE(FAIL)}$ is the minimum gain the transistor can have according to worst case circuit analysis and $h_{FE(MIN)}$) is the manufacturer's specified minimum gain. This formulation adds some extra safety because a change in manufacturing process might reduce the average gain of transistors but the manufacturer would still insure that the minimum gain was $h_{FE(MIN)}$.

5.1.4 Radiation characterization measurements. Radiation response data for particular device types are needed for initial part selection and for the calculation of the design margins (see paragraph 5.1.6) which will be used to categorize the parts for the required applications. If satisfactory data for these purposes are not available, they will have to be obtained by new measurements. (Guidelines for performing any new measurements required are given in Appendix F.) This section will discuss the treatment of radiation response data.

Characterization measurements are measurements made on a sample of parts in order to estimate the radiation response of the population of parts. Usually, the group of parts will consist of piece parts of a single part type. For the neutron environment however, it is often possible to inclue in the group of parts which is to be characterized, several different part types which are similar in function and in response to radiation. Thus, for example, several different types of high frequency transistors may be included in a group as may also several different types of operational amplifiers. These tests measure either the neutron failure fluence or else some other parameter which has a well known statistical behavior. In the discussion that follows, well known statistical behavior will almost always be taken to mean that the fluences or the parameters measured are distributed according to a lognormal law. In the rest of this document, distributions will be assumed to be lognormal. However, when data are collected, they should be plotted on lognormal paper to verify that they really are lognormal (See Appendix E). In addition, the data may be subjected to standard statistical tests (see reference 7). Most important of all, the data should be carefully examined to make sure that there are no systematic deviations from lognormality.

5.1.4.1 Selection of parts for a characterization measurement. It is important to select as many parts as practicable in a way such that the parts represent a random sampling over the entire group of parts which are being characterized. It is highly desirable for a characterization measurement to include devices from different lots and from a representative group of manufacturers. If it is impractical to obtain such a representative sample, parts from a single manufacturere may be used for characterizing a particular part type only if there is some estimate from past experience for lot-to-lot variations, manufacturer-to-manufacturer variations, and variations over an extended time period. Such estimates must be included with the standard deviation of the part's radiation response and should be justified in the HADD.

5.1.4.1.1 Sample sizes. It is important from statistical considerations that as many devices as practicable be used for radiation characterization measurements. A good test would include about 25 parts and 50 parts would be better. An absolute minimum would be 5 parts, such a small number being used only when the parts are difficult to obtain or the tests are very expensive. A small number of parts, such as five for example, could lead to a poor and possibly erroneous characterization. Furthermore, since the criteria for categorizing parts may depend on statistical considerations, the use of a small number of parts may result in devices being categorized as HCC-1 (lot acceptance testing required) simply because wide statistical uncertainties will lead to requiring larger design margins. It is worth noting therefore, that a small sample size may turn out to be an expensive "economy".

5.1.4.2 Collection and evaluation of data.

5.1.4.2.1 Measurement of fluences-to-failure. The recommended procedure for characterization measurements is to measure the radiation fluences-to-failure. Fluence-to-failure measurements require the value of PAR_{FAIL} obtained from a worst case circuit analysis (discussed in paragraph 5.1.3.1). The critical parameter is

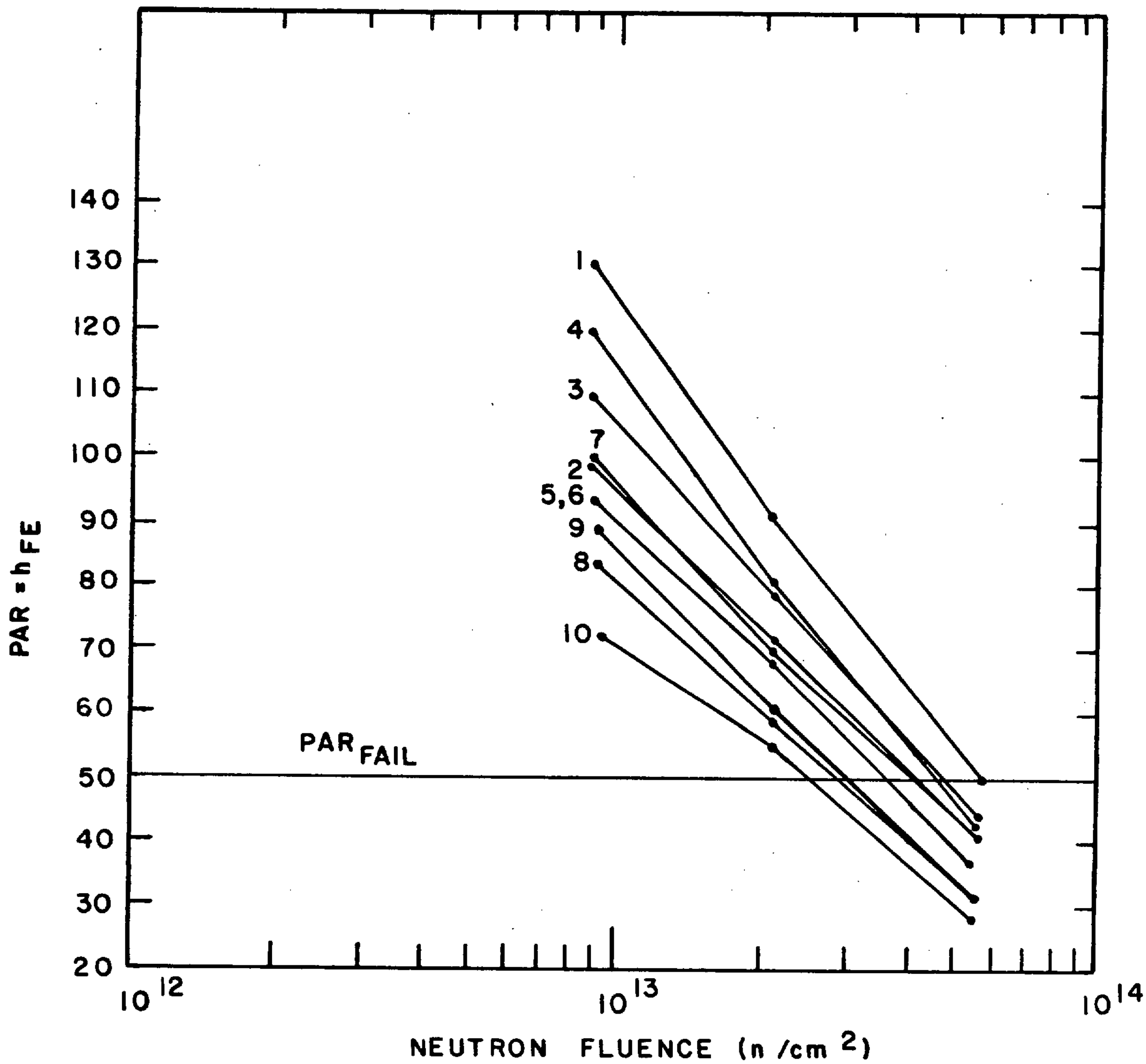

FIGURE 1. Fluence-to-failure measurements for 10 2N2222 transistors.

measured at several fluences and a curve of the corresponding parameter values vs. fluence is plotted for each device. The failure fluences are then obtained by finding where these curves cross the value PAR_{FAIL}. An example is given in Figure 1 where the gains of ten 2N2222 transistors are plotted as a function of fluence. The failure criterion in this case was

$$PAR_{FAIL} = h_{FE(FAIL)} = 55.0.$$

Note that this example is used only for illustrating the most general case. In the particular case of silicon transistors, it would be better to use $\Delta(1/h_{FE})$ as the parameter since it is known to be linear with neutron fluence.

An effort should be made to run the tests up to fluences which are sufficiently large so as to make all devices achieve PAR_{FAIL}. However, there may be cases where this is not possible and where only a portion of the devices has failed. In such a case, if a sufficient number of devices have failed, then the fluences-to-failure of those devices can be used. If the test has been run up to ten times the specification fluence ϕ_{SPEC} and less than five devices have failed then the characterization should be done in terms of the values of the parameter PAR at the fluence ϕ_{SPEC} (as outlined in paragraph 5.1.4.2.2) instead of in terms of failure fluences.

Two important quantitites are obtained from the characterization measurements. The first is the mean fluence-to-failure, ϕ_{MF}, which is given by:

$$\phi_{MF} = e^{\overline{\ln\phi_{FAIL}}} \qquad \text{Eq. 5.1.4-1}$$

where,

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

where n is the sample size and $\phi_{FAIL}(i)$ is the fluence-to-failure for the i-th part. The fluence, ϕ_{MF}, is used for the calculation of design margins which will be discussed in paragraph 5.1.6. The second quantity is the standard deviation of the fluences-to-failure $S_{1n\phi}$ which is given by:

$$S_{1n\phi} = \left\{ \frac{1}{n-1} \sum_{i=1}^{n} \left[\ln(\phi_{FAIL})_i - \ln(\phi_{MF}) \right]^2 \right\}^{1/2} \qquad \text{Eq. 5.1.4.2}$$

The standard deviation, $S_{1n\phi}$ is used for calculations of the part categoratization criteria which are also discussed in paragraph 5.1.6.

5.1.4.2.2 Measurement of parameters other than fluence-to-failure. In some cases, it may be more practical to measure a particular parameter at the specification fluence. For example, in the case of bipolar silicon transistors, it is usually more convenient to use the device damage factors (which relate gain degradation to fluence) for a characterization test. A considerable body of information already exists on these constants and they have been shown to follow a lognormal distribution.

In analogy with equations 5.1.4-1 and 5.1.4-2 we have for a parameter measurement

$$PAR_M(\phi_{SPEC}) = \exp\left\{ \frac{1}{n} \sum_{i=1}^{n} \ln\left[PAR_i(\phi_{SPEC}) \right] \right\} \qquad \text{Eq. 5.1.4.3}$$

$$S_{\ln PAR} = \left\{ \frac{1}{n-1} \sum_{i=1}^{n} \left[\ln(PAR_i(\phi_{SPEC}) - \left(\ln PAR_M(\phi_{SPEC}) \right) \right]^2 \right\}^{1/2} \quad \text{Eq. 5.1.4-4}$$

5.1.4.2.3 An example - fluence-to-failure measurement. The data for a fluence-to-failure characterization measurement on twenty 2N2222 transistors chosen from two different lots are given in Table I. Ideally, even more transistors should be used and should be taken from a more representative number of lots, but for illustrative purposes these data suffice to bring out all the necessary points. A cumulative plot of the logarithms of the fluences-to-failure on normal probability paper is shown in figure 2. The data seem to fit the lognormal distribtuion quite well and there do not seem to be any systematic deviations from the lognormal form. However, statistical tests would show that the two lots are clearly not drawn from the same parent population. Because such a result is not uncommon, a method for taking it into account is given in Appendix E.

It should be noted in passing that a characterization test on silicon transistors would normally use the theory given in Appendix A (namely that $\Delta 1/h_{FE}$ is proportional to fluence). The example given here is meant to illustrate the general procedure for a situaton where no theory exists. It will be possible to compare the results in the example with results obtained using the theory.

The significant results of this test to be used later in categorizing the parts are the combined average logarithm of fluence-to-failure, $\ln \phi_{MF}$ = 31.92, and the standard deviation of the logarithms for the combined distribution, $S_{\ln \phi}$ = 0.40. Note that the standard deviation of the combined distribution is considerably larger than that of either of the two lots. This is a typical result for a characterization measurement. The standard deviation is supposed to reflect the lot-to-lot and manufacturer-to-manufacturer variations as well as the variation of parts within a single lot.

5.1.4.3 Use of previous data. It should be pointed out finally that an actual characterization measurement can be avoided if there exists a considerable body of past information on the response of the devices to radiation. A good example of such a situation is the measurement of the neutron universal silicon damage constants of Messenger and Steele (reference 8) which was essentially a characterization measurement for all bipolar silicon transistors. A good starting point for locating any existing data is the Components Response Information Center, Harry Diamond Laboratories, DELHD-NW-RH, Adelphi, MD. Other data banks which may be useful are those maintained by the Boeing Corp., Seattle, WA (CHAP and 3260 Databanks), JPL, Pasadena, CA, (Radiation Design Handbook), IRT Corp., San Diego, CA and DASIAC at KAMAN-TEMPO in Santa Barbara, CA.

TABLE I. Fluence-to-failure for twenty 2N2222 transistors chosen from two different lots.

Failure criterion $h_{FE(FAIL)}$ = 40			
Lot 1		Lot 2	
ϕ_{FAIL} (10^{13}n/cm^2)	ln ϕ_{FAIL}	ϕ_{FAIL} (10^{13}n/cm^2)	ln ϕ_{FAIL}
7.77	31.98	7.86	32.00
6.12	31.75	8.92	32.12
6.38	31.78	8.71	32.35
6.15	31.75	11.23	32.10
5.04	31.55	8.25	32.04
5.00	31.54	11.08	32.34
5.02	31.55	10.53	32.29

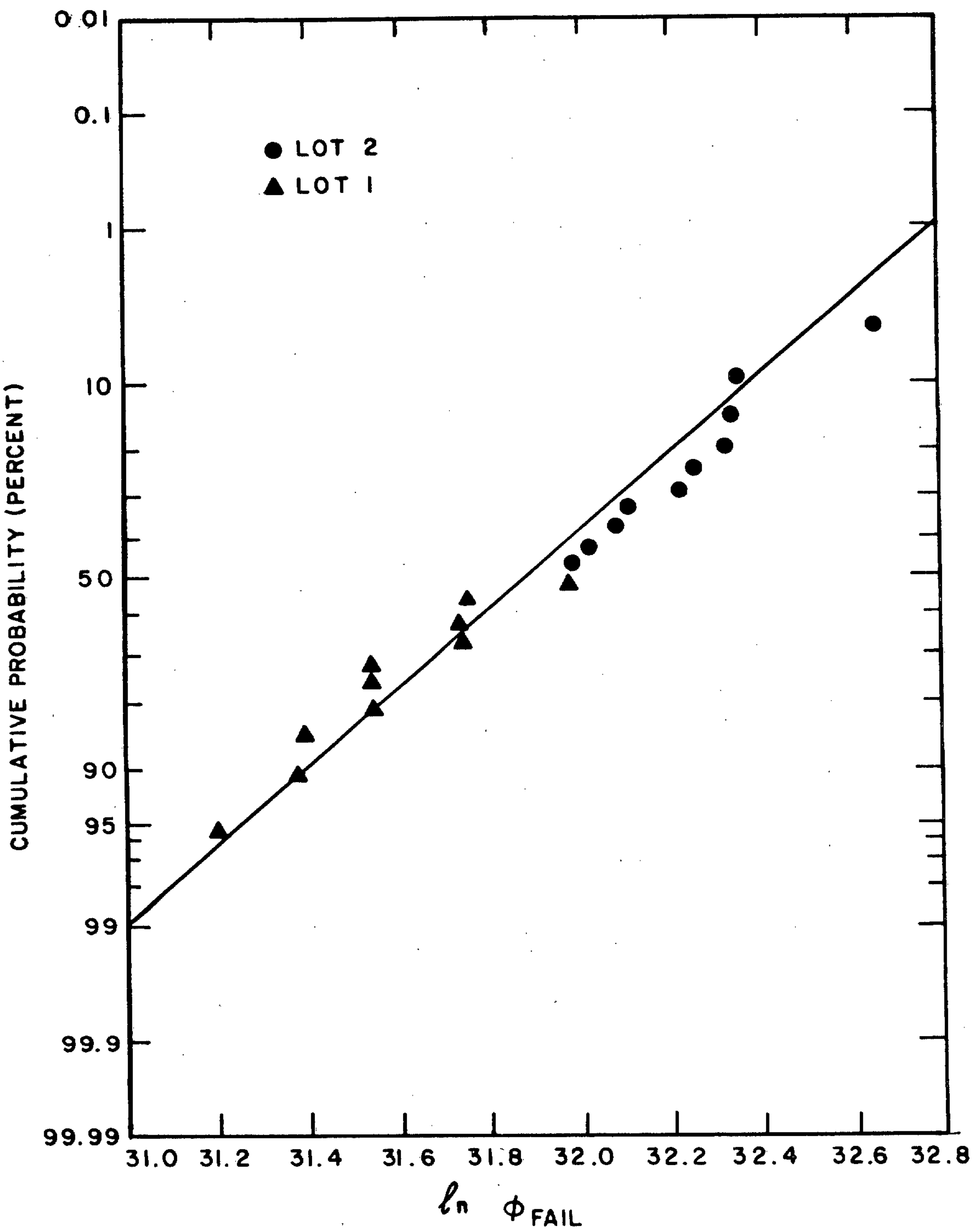

FIGURE 2. <u>Cumulative plot on normal probability paper of the logarithms of fluences-to-failure of 20 2N2222 transistors drawn from 2 lots (see table I).</u>

Table I. Fluence-to-failure for twenty 2N2222 transistors chosen from two different lots - Continued.

Failure criterion $h_{FE(FAIL)} = 40$			
Lot 1 (Cont'd)		Lot 2 (Cont'd)	
4.25	31.38	10.00	32.24
4.33	31.41	11.43	32.37
3.60	31.21	15.56	32.68
Avg: $\ln\phi_{FAIL}$	31.59		32.25
Standard Dev: $S_{\ln\phi}$	.23		.20
Both lots combined			
Avg: $\ln\phi_{FAIL}$	31.92		
Standard Dev: $S_{\ln\phi}$	0.40		

5.1.5 Design margins. In its usual sense, a design margin is an extra factor built into a system to account for unknown factors which might cause failure. It may be assumed that one hundred percent safety can never be guaranteed. The design margin required for a given application is based therefore on balancing the consequences of failure against the cost involved in reducing the risk. The choice of the required design margin is based on calculations, past experience, and judgement. The definitions of design margins, discussed in the sections which follow, have been chosen to facilitate hardness assurance calculations.

5.1.5.1 Neutron design margin (NDM) - A design margin based on fluence-to-failure. In this document, the neutron design margin is defined as

$$NDM = \phi_{MF} / \phi_{SPEC} \qquad \text{Eq. 5.1.5-1}$$

where ϕ_{MF} is the geometric mean of the fluence to failure given by Eq. 5.1.4-1.

a. This definition is based on fluence-to-failure and is useful even when some mechanism other than gain degradation is responsible for the device failure.

b. The probability distribution for fluences-to-failure approximates a lognormal, rather than a normal distribution, so the use of the geometric rather than an arithmetic mean is appropriate.

The neutron design margin, NDM, is compared with categorization criteria for purposes of categorizing parts as belonging to hardness critical category 1 or to hardness critical category 2. This topic is discussed in detail in paragraph 5.1.6.

5.1.5.2 Parameter design margins. Though it will generally be less useful than the Neutron Design Margin, a design margin for any parameter can also be defined.

When the parameter decreases with fluence,

$$DM(PAR) = PAR_M(\phi_{SPEC})/PAR_{FAIL} \qquad \text{Eq. 5.1.5-2}$$

and when the parameter increases with fluence,

$$DM(PAR) \equiv PAR_{FAIL}/PAR_M(\phi_{SPEC}) \qquad \text{Eq. 5.1.5-3}$$

where the subscript M denotes geometric means.

In the case of the device damage factors, K_D, discussed in Appendix A, it is $(K_D)_{FAIL}$ which changes with the specified neutron fluence ϕ_{SPEC} while the device damage factor depends on the specific devices in the test but not on the neutron fluence. In such cases

$$DM(PAR) = (K_D)_{FAIL}(\phi_{SPEC})/(K_D)_M \qquad \text{Eq. 5.1.5-4}$$

where again the subscript M denotes geometric means.

5.1.6 <u>Determination of design margin break points and part categorization criteria.</u> Parts are categorized by comparing design margins with either a Design Margin Break Point or Part Categorizaton Criteria. Such categorization may be performed on the basis of neutron design margins or parameter design margins. In the following paragraphs, discussions will be given of the two methods mentioned, namely the DMBP method that applies to systems with moderate requirements and the Part Categorization Criteria method that applies to systems with more stringent requirements. (See paragraph 5.1.1.1)

5.1.6.1 <u>Part categorization criteria for the design margin break point (DMBP) method - systems with moderate requirements.</u> For systems with moderate requirements, a single categorization criterion, called a DMBP, is used for all parts in the system. The DMBP is usually determined from the required survivability of piece parts and worst case estimates of the standard deviations in fluence-to-failure of any part type in the system. Since parts which more than meet the survivability requirements should be easily obtained, estimates should err on the conservative side wherever estimates are made. An example of such a procedure is:

a. Assuming a lognormal distribution and considering all part types, estimate with confidence, C, the worst case standard deviation, S_{1n}, in the logarithms of the fluences-to-failure. Any error in this estimate should be in the direction of an over-estimate.

b. Using standard statistics tables, and the required survival probability, P, look up $\bar{F}_n(P)$ which correspnds to the number of standard deviations above the mean of a normal distribution which includes fraction P of the distribution ($\bar{F}_n(P)$ is the antifunction of the cumulative standard normal probability distribution; as an example for P = 0.9, $\bar{F}_n(P)$ = 1.282).

c. Get the DMBP from

$$DMBP = e^{\bar{F}_n(P)\, S_{1n}} \qquad \text{Eq. 5.1.6-1}$$

5.1.6.1.1 <u>Estimating DMBP for bipolar Si Transistors.</u> In the absence of any other information, <u>a worst case estimate of S_{1n} may be obtained</u> from the data of Messenger and Steele and an analysis by A. Namenson as follows (see references 8 and 9):

$$S_{1n} \approx 0.423 \left[1 + 0.12\ \bar{F}_n(C) + .00969\ \bar{F}_n(C)^2\right]$$

5.1.6.1.2 <u>Example of the DMBP method used in practice.</u> The U.S. Air Force <u>(references 2 and 3) uses the criteria given in Table II.</u>

For bipolar S_i transistors, a DMBP of 10 corresponds approximately to 90 percent confidence that less than 1 X 10^{-6} parts will fail at ϕ_{SPEC}. The DMBP of 100 is based on previous experience which has shown that parts whose NDM exceed this value are clearly non critical.

TABLE II. Example of design margin break points (DMBPs)

Category	Requirement on design margin
HCC-1	Design margin < 10
HCC-2	10 $\leq$ Design margin $\leq$ 100
Non-critical	Design margin > 100

5.1.6.2 Systems with stringent requirements - PCC method. If a system has stringent requirements, then a separate decision must be made about the risk to be taken for each part type and different categorizaion criteria must be developed for each part type. Usually there will be only a few critical part types which will be likely to cause system failure. For such part types, an estimate must be made in quantitative terms of how important it is that they survive. Such an estimate is usually expressed as a confidence level, C, that a certain part will have at least a probability, P, of surviving in the specified neutron fluence. For this confidence and probability and the number of parts to be used, it is possible to calculate the probability of system survival.

The PCC method generally lowers the part categorization criteria because the design margins in the DMBP approach usually apply worst case assumptions about the variability in the parts of a given type to the most neutron sensitive parts of the system. In practice, most part types will have much narrower population distributions and such lower sensitivity to neutrons than assumed in the DMBP approach.

In the PCC method, the actual values calculated for PCC may be expected to be different for different systems. They are determined from the characterization measurements discussed in paragraph 5.1.5 through the application of statistical analyses and the survival probability and confidence level requirements developed during system design and hardening. Neutron design margins, NDM, as defined in Eq. 5.1.5-1, or DM(PAR) as defined in Eqs. 5.1.5-2 and 5.1.5-3 are then compared to the categorization criteria to determine part categories. Parts with design margins over 100 (or some lower number if one can be justified) will be considered non-critical, as has been discussed in paragraph 5.1.6.1.2.

The quantities required to calculate part categorization criteria are the standard deviation, S_{1n}, of the logarithms of parameter measurements or of fluences-to-failure, the number of devices, n, used for the characterization measurements, the required survival probability, P, and the confidence level, C. When fluences-to-failure are measured, S_{1n} is $S_{1n\phi}$, the standard deviation in the logarithms of the fluences-to-failure as given in Eq. 5.1.4-2. If a parameter is measured, S_{1n} is S_{1nPAR}, the standard deviations in the logarithms of the parameter at the fluence ϕ_{SPEC} as given in Eq. 5.1.4-4. It is assumed that the individual piece part fluence-to-failure values (or parameter values when a parameter measurement is made) obey a lognormal probaiblity distribution. (The consequences of deviations from log normality or of uncertainties about the distribution can be most important and should not be overlooked. These factors are discussed in detail in Appendix E and will not be included in this section.) PCC is now calculated by means of one of the expressions:

$$PCC = e^{K_{TL}(n,C,P)\, S_{1n\phi}} \quad \text{or} \quad PCC = e^{K_{TL}(n,C,P) S_{1nPAR}} \qquad \text{Eq. 5.1.6-2}$$

where $K_{TL}(n,C,P)$ is the one sided tolerance limit factor for normal distributions. Values for K_{TL} are given in Appendix E.

5.1.6.2.1 An example - part categorization calculations for a 2N2222 transistor - use of measured neutron fluences-to-failure. In this example, all the calculations required for categorizing a 2N2222 transistor will be explicitly shown. The fluence-to-failure data used will be that given in Table I for a characterization measurement on twenty 2n2222 transistors. The specification fluence is taken to be 1.0 X 10^{13} n/cm^2 (1-MeV silicon equivalent) and the required survival probability and confidence levels are taken to be .9999 and 0.9 respectively.

The first quantity required is the design margin NDM. The data of Table I and Eq. 5.1.4-1 give

$$\phi_{MF} = e^{31.92} = 7.29 \times 10^{13}\ n/cm^2.$$

Therefore,

$$NDM = \phi_{MF}/\phi_{SPEC} = 7.3 \times 10^{13} / 1.0 \times 10^{13} = 7.30$$

Next, the part categorization criterion PCC is obtained from Eq. 5.1.6-1 so values are needed for the standard deviation, $S_{ln\phi}$, of the fluences-to-failure and for the one sided tolerance limit factor $K_{TL}(n,C,P)$. The combined standard deviation, given in Table I is 0.40. The value of K_{TL} given in the table in Appendix E is:

$$K_{TL}\ (n=20,\ C = .9,\ p = .9999) = 4.802.$$

Eq. 5.1.6-1 then gives:

$$PCC = e^{4.802 \times 0.40} = 6.83$$

Since NDM is 7.30, the part belongs in HCC-2.

5.1.6.2.2 An example - part categorization calculations for a 2N2222 transistor using a parameter - the device damage factors K_D - same set of transistors as those used in paragraph 5.1.6.2.1. The same twenty 2N2222 transistors as those used in the preceding paragraph will again be characterized, but now on the basis of the device damage factors K_D defined in Appendix A as:

$$1/h_{FE(\phi)} - 1/h_{FE(INITIAL)} = K_D\ \phi \qquad \text{Eq. 5.1.6-3}$$

where $h_{FE(INITIAL)}$ is the current gain of the transistor before irradiation, $h_{FE(\phi)}$ is the current gain after irradiation, and ϕ is the irradiation neutron fluence.

From a large amount of background information (reference 8), it is known that the transistor device damage factors follow a lognormal distribution.

As in the previous example, the specified neutron fluence is 1.0 X 10^{13} n/cm^2 and the transistor is considered to fail if its current gain h_{FE} goes below 40 (See Table I). Since the device damage factor is a property of a transistor and does not depend on neutron fluence, Eq. 5.1.5-4 will apply. K_{DM} and $K_{D(FAIL)}(\phi_{SPEC})$ are required. Each of these quantities will be calculated below.

The mean (geometric) device damage factor, K_{DM}, is calculated from Eq. 5.1.4-3 and this calculation requires the device damage factors of all the transistors. To obtain the device damage factor for the i-th transistor from the measurements, Eq. 5.1.6-1 must be rewritten as:

$$(K_D)_i = \left[1/h_{FE}(\phi_i) - 1/h_{FE(INITIAL)} \right] / \phi \qquad \text{Eq. 5.1.6-4}$$

Table III now presents the device damage factors obtained from Eq. 5.1.6-2.

The failure limit of K_D is obtained from:

$$K_{D(FAIL)} \equiv \left[1/h_{FE(FAIL)} - 1/h_{FE(MIN)} \right] / \phi_{SPEC} \qquad \text{Eq. 5.1.6-5}$$

where $h_{FE(MIN)}$ is the manufacturer's specified minimum current gain.

With the manufacturer's specified minimum gain of $h_{FE(MIN)} = 75$, the failure value of $h_{FE(FAIL)} = 40$, and the neutron fluence of $\phi = 1.0 \times 10^{13}$ n/cm^2,

$$K_{D(FAIL)} = 1.167 \times 10^{-15}.$$

TABLE III. Device damage factors, K_D, for Twenty 2N2222 transistors chosen from two different lots. 1/

Lot 1		Lot 2	
K_D (10^{-16}cm^2/n)	$\ln K_D$	K_D (10^{-16}cm^2/n)	$\ln K_D$
2.31	-36.55	2.6	-35.89
2.04	-36.21	2.9	-35.78
2.11	-36.30	3.0	-35.74
1.67	-36.01	3.2	-35.68
2.30	-36.33	3.5	-35.59
1.75	-36.13	3.6	-35.56
1.87	-36.15	3.7	-35.53
2.00	-36.28	4.0	-35.45
1.71	-36.09	4.1	-35.43
1.34	-36.00	4.3	-35.38
Avg: $\ln K_D$	-36.21		-35.60
Standard Dev: $S_{\ln}(K_D)$	0.17		0.16
Both lots combined			
Avg: $\ln K_D$	-35.90		
Standard Dev: $S_{\ln}(K_D)$	0.35		

1/ The device damage factors in this table are calculated for the same transistors as those used for Table I.

From Table III, the geometric mean of K_D is,

$$K_{DM} = \exp\overline{(\ln K_D)} = 2.551 \times 10^{-16}$$

and, since $K_{D(FAIL)}$ decreases with fluence, Eq. 5.1.5-5 must be used to give a design margin for K_D:

$$DM(K_D) = K_{D(FAIL)}/(K_D)_M = 4.58.$$

For a survival probability of 0.9999 with confidence 0.9, K_{TL} is again given by

$$K_{TL}\ (n = 20,\ C = 0.9,\ P = 0.9999) = 4.802$$

To get the acceptance criterion PCC, Eq. 5.1.6-1 is again used with the value of $S_{1n}(K_D) = 0.35$ being taken from Table III. Therefore,

$$PCC = e^{4.802 \times 0.35} = 5.34$$

So the part must be categorized as HCC-1.

5.1.6.2.3 Correcting the sample size. In many instance, test data, while showing no systematic deviaton from the lognormal distribution, may nevertheless show a poor fit to this type of distribution. In such cases, there is an "effective" sample size, as explained in reference 9 and also in Appendix E, which is smaller than the actual number of devices tested. This situation arises commonly because manufacturer-to-manufacturer or even wafer-to-wafer variations are larger than variations between individual devices from the same manufacturer or wafer. In these cases, the real sample size will be the number of manufacturers or the number of wafers. For illustrative purposes, the methods of reference 9 were used to perform a detailed analysis on the data in Table I. The best estimate for the "effective" sample size turned out to be 13 even though the number of transistors tested was 20. For n = 13, K_{TL} may be found from the tables given in Appendix E, to be:

$$K_{TL}(n = 13,\ C = 0.9,\ P = 0.9999) = 5.196.$$

With a standard deviation of 0.4 again taken from Table I, PCC becomes:

$$PCC = e^{5.196 \times 0.4} = 8.00$$

For the first example (paragraph 5.1.6.2.1), where the design margin was 7.3, the increase in the PCC from 6.83 to 8.00 would change the part category from HCC-2 to HCC-1. This example, therefore serves to illustrate that there are some cases where properly correcting for the sample size can change the part category. There is, however, some utility to using the uncorrected sample size since, if a part does not qualify for HCC-2 on that basis, then there is no need to perform the more difficult calculation. Such a situation is illustrated by the second example (paragraph 5.1.6.2.2) where the part would remain in HCC-1 even if the sample size correction were performed.

5.1.6.2.4 Part categorization criteria and design margins for bipolar transistors - use of a previously derived univeral silicon damage constant and the manufacturer's specifications - general discussion and an example. An extensive background of previous information often makes it possible to categorize parts without new measurements or else with only minimal measurements. A variety of strategems may be used to replace costly measurements by calculations. This is an entire topic in itself with many ramificatons. One simple example will be given here. A more complete discussion is given in Appendix A.

Essentially, the measurements of Messenger and Steele (reference 8) are a radiation characterization test which considered all silicon bipolar transistors to be a single class of devices. On the basis of these measurements and on the basis of the assumptions and reasoning outlined in Appendix A, a worst case estimate of the design margin $DM(K_D, MIN)$ for the device damage factor K_D is derived in Appendix A and given by Eq. 5.1.6-3. It will be assumed that the transistors are operated near a maximum current gain point of 200 A/cm^2. From Figure 4 in Appendix A, the universal silicon damage constant at this current density may be taken to be $0.65X10^{-6}$. Thus,

$$DM(K_D, MIN) = 2\pi f_{T(MIN)} \frac{1/h_{FE(FAIL)} - 1/h_{FE(MIN)}}{0.65 \times 10^{-6} \quad \phi_{SPEC}} \qquad \text{Eq. 5.1.6-6}$$

where $h_{FE(MIN)}$ and $f_{T(MIN)}$ are both determined from the manufacturer's specifications.

The remainder of this calculation applies only to the case where the minimum $DM(K_D)$ has been estimated as above.

The data of Messenger and Steele (reference 8) yield, for the standard deviation of the universal silicon damage constant, the value $S_{ln}(K_D) = 0.423$, and an "effective" sample size n = 53 (reference 9). The categorization criterion for bipolar silicon transistors then becomes:

$$PCC = \exp \; K_{TL}(n{=}53,C,P) \times 0.423 \quad . \qquad \text{Eq. 5.1.6-7}$$

Table IV gives values of PCC for some of the most commonly used confidences and failure probabilities, (1-P).

If the minimum possible design margin as determined from Eq. 5.1.6-3 is greater than the part categorization criterion (as found from either Eq. 5.1.6-4, or Table IV) then the part may be categorized as HCC-2. It is interesting to note that a PCC of about 10, the value which is used in the Design Margin Breakpoint Method discussed in paragraph 5.1.6.1.2, corresponds to a failure probability of less than 10^{-6} with a confidence of 0.9. This value is more than adequate in most applications for categorizing a part as HCC-2.

TABLE IV. Confidence levels.

1-P	0.9	0.95	0.99	0.999
.1	1.9	2.0	2.1	2.2
.01	3.1	3.4	3.8	4.4
10^{-3}	4.6	5.0	5.8	7.0
10^{-4}	6.3	6.8	8.2	11
10^{-5}	8.2	9.0	11	5
10^{-6}	11	12	15	20

Values of PCC for Various Confidence Levels and Failure Probabilities (1-P); Calculations based on Eq. 5.1.6-7

An example: The minimum estimate of DM and values of PCC from Table IV can now be used to categorize the 2N2222 transistors. For this transistor type, the manufacturers specifications are $f_{T(MIN)} = 2.5 \times 10^8$ Hz and $h_{FE(MIN)} = 75$. Once again the specificaton fluence, ϕ_{SPEC}, will be taken to be 1.0×10^{13}. Substitution of these values into Eq. 5.1.6-2 gives

$$DM(K_D,MIN) = 2\pi \times 2.5X10^8 \frac{1/40 - 1/75}{0.65X10^{-6} \times 1.0X10^{13}} = 2.8.$$

As in the previous examples we will again assume for illustrative purposes that with confidence C = 0.9 the survival probability must be P = 0.9999. For these values, PCC is given in Table IV to be 6.3. A comparison of $DM(K_D, MIN) = 2.8$ with the value 6.3 shows that, for this example, this part type is in HCC-1.

5.2 Radiation hardness assurance. This section will discuss the procedures that are to be used for the procurement and installation of devices once the system or circuit hardened design has been developed and the parts to be used have been selected. It will be assumed here that the parts to be used will have been characterized and categorized and, further, that the required piece part survival probabilities and confidence levels to be used for lot acceptance testing will have been set during the design hardening phase. It is worth emphasizing a point made earlier, namely that the piece part documentation prepared during design hardening i.e. the hardness assurance design documentation (HADD), must include all the information which will be needed to implement hardness assurance procedures. If it does not, many of the measurements and calculations made at that time will have to be repeated as part of the hardness assurance program.

As outlined in paragraph 5.1.2 the hardness assurance plan may require checking for the presence of all HCC-1H parts in their required circuit locations. For HCC-1M parts, the plan may require that the part come from a particular vendor, or an electrical screen, or a lot acceptance test or a combination of the above.

5.2.1 Lot acceptance tests. When parts are selected for a lot acceptance test, some attempt should be made to get a representative random sample. For example, if a shipment comes in several packages, representative parts should be taken from as many different packages as possible.

An important warning should also be mentioned. If a large fraction of the lots (comparable to the desired confidence level c) is rejected, then it is likely that even those few lots which passed the lot acceptance tests are also defective. In such a case, consideration should be given to looking for an alternative part type, to using electrical screens, and/or to circuit hardening.

It should be pointed out that the data resulting from each test is potentially useful information for a data bank. Every effort should be made to have the neutron response data submitted to a service or DOD data bank for access by others.

Two general methods may be used for lot acceptance tests. The first is called an attribute sampling test method or, commonly, a lot tolerance percent defective (LTPD) test. This test determines how many devices out of a given sample size have failed under test conditions. A description of this method is given in Appendix E. The LTPD method is widely used for quality assurance. It is simple to use but requires inordinately large sample sizes when low failure probabilities are needed. For example, to allow prediction of a failure probability of 1 in 10^4 at 90 percent confidence, 2,000 sample parts would have to be tested with no failures. An exception to these comments is that it may be possible to obtain high survival probabilities with a small sample size by performing an LTPD overtest at several times the specification fluence; the extrapolation to higher survival probabilities at the specification fluence requires a knowledge of the distribution. The second method, called a variable sampling test method, determines the statistical behavior of a variable (for example fluence-to-failure or PAR_ϕ) under test conditions. This method has the advantage of being able to predict a low failure probability, with high confidence, on the basis of a relatively small sample size. It has the disadvantage that it requires assumptions about the probability distribution of the variable involved. Such assumpations are usually reasonable however, and the advantage of being able to use sample sizes which are easily attainable far outweighs any disadvantages.

5.2.1.1 Lot acceptance tests using fluence-to-failure. Consider a lot sample size of n randomly selected parts, a specified neutron fluence of ϕ_{SPEC}, a required survival probability of P, and a required confidence level of C. The fluence-to-failure must be measured for each part and from these measurements ϕ_{MF}, the geometric mean failure fluence as defined in Eq. 5.1.4-1, will be obtained along with

$S_{ln\phi}$, the standard deviation as defined in Eq. 5.1.4-2. To identify these quantities as belonging to the actual lot being procured and different from the ϕ_{MF} and $S_{ln\phi}$ determined in the characterizaton measurements, they are here designated as $\phi_{MF}(LOT)$ and $S_{ln\phi}(LOT)$. The lot acceptance criterion is then given by:

$$NDM\ (LOT) = \frac{\phi_{MF}(LOT)}{\phi_{SPEC}} \geq e^{K_{TL}(n,C,P)S_{ln\phi}(LOT)} \qquad \text{Eq. 5.2.1-1}$$

where, as before, K_{TL} is the one sided tolerance limit factor. This equation has been obtained on the basis of the analysis given in Appendix E and is similar to the analysis used for characterization tests.

5.2.1.1.1 An example - lot acceptance tests using fluence to failure. A lot acceptance test is considered where it is required that with confidence 0.90, at least a fraction 0.9999 of the parts will survive a fluence of 2.5 X 10^{13} n/cm^2. Lot 2 of Table I will be considered to be the lot under test. For that lot,

$$\phi_{MF}(LOT\text{-}2) = e^{32.25} = 1.01 \times 10^{14}\ n/cm^2.$$

NDM then is,

$$NDM(LOT) = 1.01 \times 10^{14}/2.5 \times 10^{13} = 4.04$$

Also for Lot-2, Table I gives

$$S_{ln\phi}(LOT\text{-}2) = 0.2.$$

For a sample size of 10, the value for K_{TL} found from the tables given in Appendix E is

$$K_{TL}(n = 10,\ C = 0.9,\ P = 0.9999) = 5.54$$

and the lot acceptance criterion then is

$$NDM \geq e^{5.54 \times 0.2} = 3.03.$$

Because NDM = 4.04, lot-2 is accepted.

5.2.1.2 Lot acceptance tests using a parameter. This method applies to cases where fluence-to-failure measurements are not practical and where it would be a great saving in cost simply to measure a parameter at a single fluence, namely ϕ_{SPEC}, for a group of piece parts. The statistical analysis would then be performed on this parameter. The risk in using this method is that the population distribution may not turn out to be a lognormal distribution.

Under the assumption that the distribution is lognormal, the analysis is exactly the same as for fluence-to-failure. The required lot acceptance criterion in this case is

$$DM(PAR, LOT) = \frac{PAR_M(\phi_{SPEC}, LOT)}{PAR_{FAIL}} \geq e^{K_{TL}(n,\ C,\ P)\ S_{lnPAR}(LOT)} \qquad \text{Eq. 5.2.1-2}$$

where the quantities $PAR_M(\phi_{SPEC})$ and S_{lnPAR} are defined in Eqs. 5.1.4-3 and 5.1.4-4.

5.2.1.2.1 An example - lot acceptance tests using a parameter, the gain, of 2N2222 transistors. Once again the problem of testing a lot of 2N2222 transistors is considered. The specified neutron fluence is 2.5×10^{13} n/cm^2, and it is required that, with confidence 0.90, at least a fraction 0.9999 of the transistors in an accepted lot will survive the specified fluence. The gain at which the circuit will fail is given as:

$$PAR_{FAIL} = h_{FE(FAIL)} = 40.$$

Table V shows a measurement of h_{FE} for ten 2N2222 transistors at a fluence of 2.5×10^{13} n/cm^2. From this table

$$\overline{e^{\ln h_{FE}(\phi_{SPEC})}} = 95.6.$$

In this case then,

$$DM(h_{FE}, LOT) = 95.6/40 = 2.39.$$

Once again, the value for K_{TL} may be obtained from the tables in Appendix E. Thus

$$K_{TL}\ (n = 10,\ C = 0.9,\ P = 0.9999) = 5.54$$

and, from Table V,

$$S_{\ln h_{FE}}(LOT) = 0.145.$$

The lot acceptance criterion, Eq. 5.2.1-2, therefore becomes

$$DM(h_{FE}, LOT) \geq e^{5.54 \times 0.145} = 2.23$$

and since $DM(h_{FE}, LOT)$ is 2.39, the lot is accepted.

Table V. Radiation Lot Sample Date for Ten 2N2222 Transistors at a Neutron Fluence of $\phi_{SPEC} = 2.5 \times 10^{13}$ n/cm^2.

Transistor	$h_{FE(RAD)}$	ln $h_{FE(RAD)}$
1	78	4.36
2	84	4.43
3	84	4.43
4	96	4.56
5	85	4.44
6	100	4.61
7	100	4.61
8	100	4.61
10	125	4.83

$$\overline{\ln h_{FE}(\phi_{SPEC})} = 4.56$$

$$S_{\ln h_{FE}} = 0.145$$

$$\text{Geometric Mean} = e^{\overline{\ln h_{FE}(\phi_{SPEC})}} = 95.6$$

The collector Current was 10 ma and the Collector-Emitter Voltage was 5 V

Since the lognormality of the distribution $h_{FE}(\phi_{SPEC})$ may be in question, it should be checked. Figure 3 shows a cumulative plot of lnh_{FE} on normal probability paper. There is no obvious visual deviation from the lognormal form and the statistical test recommended in reference 7 confirms this conclusion. It should be emphatically noted that this is an illustrative example and, in practice, it would be unwise to calculate survival probabilities of 0.9999 on the basis of only ten transistors unless the lognormal law was established on the basis of a much larger sample size.

5.2.2 Screening parts. Often parts may be qualified by using screens instead of (or in conjunction with) lot acceptance tests. Eq. 5.1.6-3 shows that the higher $f_{T(MIN)}$ and $h_{FE(MIN)}$, the higher will be the estimated minimum design margin, $DM(K_D, MIN)$. The values of $f_{T(MIN)}$ and $h_{FE(MIN)}$ can be raised above the manufacturers specifications by performing electrical measurements and rejecting devices where f_T or h_{FE} are too low. Since such screens are non destructive, 100 percent of the installed parts can be screened. It is obvious from the example in paragraph 5.1.6.2.4 that screening can often eliminate the need for more expensive lot acceptance radiation response testing. However, even where it does not do so, it may be used to raise the probability that a lot will pass an acceptance test.

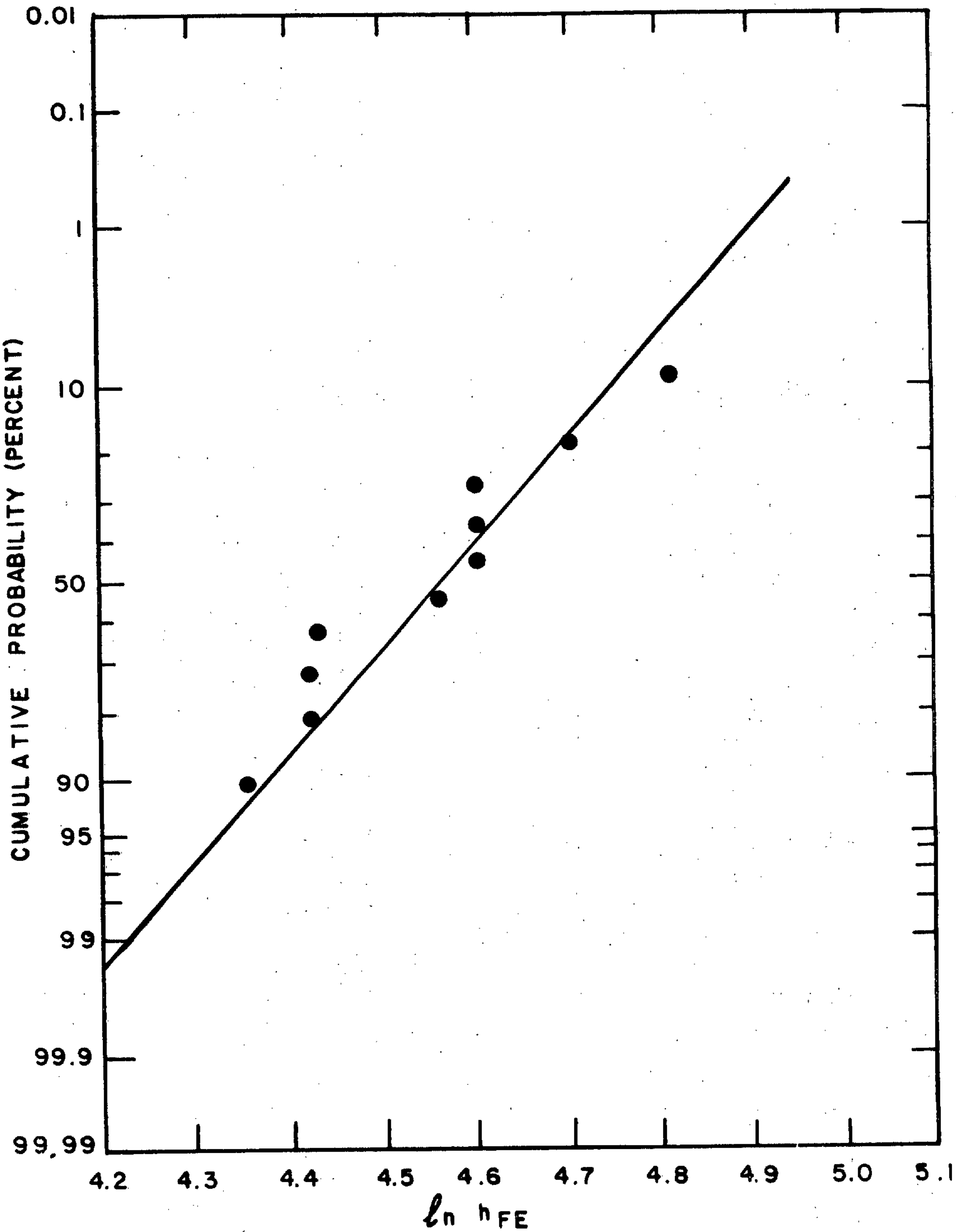

FIGURE 3. Cumulative plot on normal probability paper of the logarithms of the gains, h_{FE}, of 10 2N2222 transistors measured after irradiations by a neutron Fluence of 2.5×10^{13} n/cm^2.

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* Available from the National Technical Information Center, Springfield, VA 22161, under this order number.

† Available from the Defense Technical Information Center; Attention: DDR-1, Cameron Station, Alexandria, VA 22314, by using this order number. Tel: (202) 274-7633.

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

Preparing activity:
Navy - EC

(Project 59GP-0044)

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

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

Agent:
DLA - ES

APPENDIX A

TRANSISTOR HARDNESS ASSURANCE

10. GENERAL

10.1 Scope. This appendix provides detail data on transistor hardness assurance for silicon bipolar and junction field-effect transistors.

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. DETAILED EXAMPLES

50.1 Silicon Bipolar transistors. Neutron radiation degrades the electrical characteristics of semiconductor devices by increasing the number of trapping, scattering, and recombination centers in the semiconductor material. Trapping centers remove majority carriers from the conduction process, scattering centers reduce carrier mobility, and recombination centers decrease minority carrier lifetime.

The electrical performance of bipolar devices depends critically on the minority carrier lifetime in the base region. A decrease in this parameter due to neutron damage will cause the current gain, h_{FE}, of a transistor to decrease. It is found that the degradation of transistor reciprocal gain is approximately linear with neutron fluence for moderate collector current levels and can be described by the Messenger-Spratt equation (references A-1 and A-2).

$$\Delta\left(\frac{1}{h_{FE}}\right) = \frac{K}{2\pi f_T}\Phi, \qquad \text{Eq. 50.1-1}$$

where $\Delta(1h_{FE}) = (1/h_{FE(RAD)} - (1/h_{FEO})$,

$h_{FE(RAD)}$ is the gain after neutron irradiation,

h_{FEO} is the gain before neutron irradiation,

K is the universal silicon damage constant ($cm^2/n\cdot s$),

ϕ is the 1 MeV equivalent silicon damage neutron fluence (n/cm^2), and

f_T is the gain-bandwidth product (s^{-1}).

Estimates for values of the universal silicon damage constant, K, for bipolar silicon transistors of any type and manufacture should be obtained from Figure 4 1/ when information about K is not otherwise available for any such devices of interest. The reader is cautioned, however, that the curve provided in Figure 4 may give too low an estimate of K for some transistors at current densities above where h_{FE} is a maximum. This maximum typically occurs at a current density in the range of 100 to 1000 A/cm^2. An increase in K can occur at these high current densities due to a combination of second order effects such as emitter crowding, conductivity

1/ The shape of the dependence of K on emitter current density, J_E, is taken from a two-level model for lifetime reduction processes (references A3 and A4). The curve is normalized to a value of $K = (1/2.06)\cdot10^{-6}$ $cm^2/n\cdot s$ at very large J_E. This value of K was arrived at by analyses (references A-5 and A-6) of data from bipolar silicon transistors of a variety of types and manufacturers which were developed and extrapolated to very high current densities by Messenger and Steele (reference A-2).

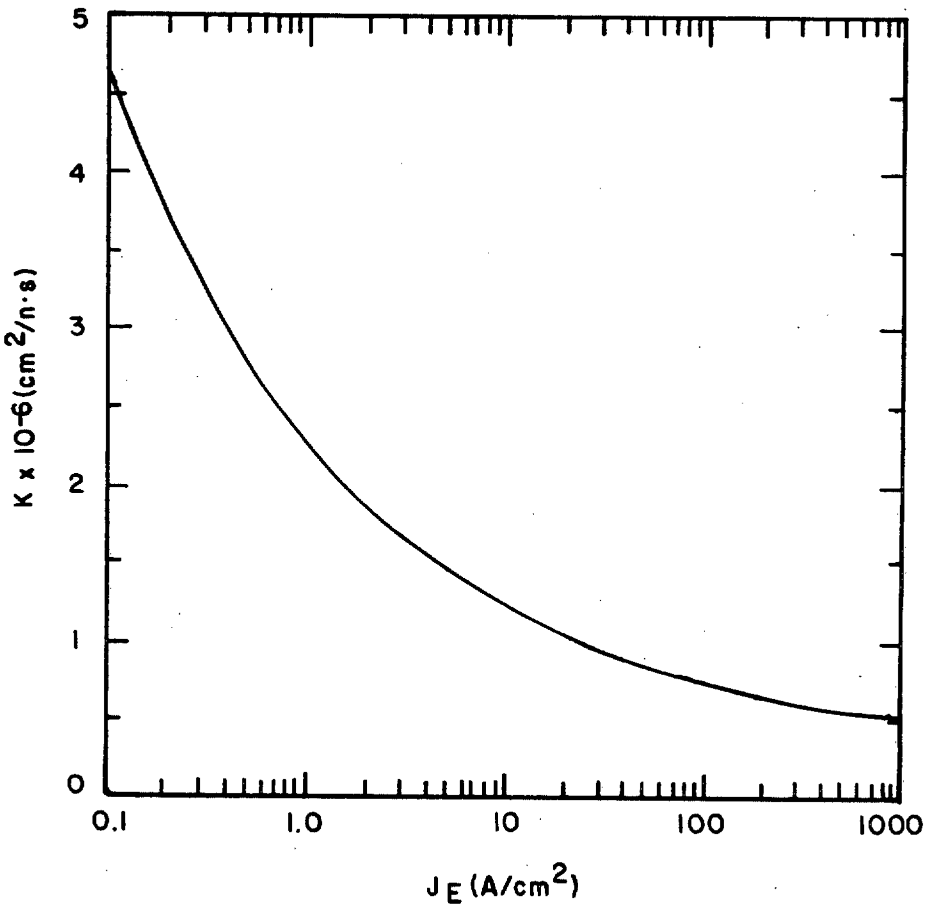

FIGURE 4. Universal silicon damage constant, K, versus emitter current density, J_E, from the expression:

$$K = \frac{1.68}{2.06} \times \frac{J_E^3 + 313J_E^2 + 6280J_E + 3410}{1.68J_E^3 + 332J_E^2 + 2850J_E + 420} \times 10^{-6}\ cm^2/n\bullet s.$$

modulation, junction heating, and other high current-density effects. These effects on K are most pronounced in devices with large emitter-area-to-perimeter ratios, for example devices with circuilar emitters, and least pronounced in transistors with small emitter-area-to-perimeter ratios, such as interdigitated power transistors. Examples of such increase in K with current density are shown by Jarl (reference A-7).

The value of K is only a weak function of the type of impurity and of the restivity for the range of resistivities commonly found in devices. K is a strong function of the neutron energy spectrum, however. The above values of K were obtained by converting neutron spectra to a 1 MeV equivalent silicon damage neutron fluence.

Transistor neutron damage is usually expressed in terms of the geometry-dependent device damage factor, K_D, which is related to K by

$$K_D = \frac{K}{2\pi f_T} \quad \text{Eq. 50.1-2}$$

Eqs. 50.1-1 and 50.1-2 can be combined to give

$$\Delta \left(\frac{1}{h_{FE}}\right) = K_D \, \Phi \, . \quad \text{Eq. 50.1-3}$$

It should be emphasized that this equation can, with the proper choice of the device damage factor, K_D, also be applied to bipolar transistors within integrated circuits or to elements of the equivalent circuit of a thyristor.

In the absence of other information, the data of Messenger and Steele (reference A-2) may be use to estimate the smallest or worst-case design margin, DM(K_D, MIN), based on the manufacturer's specifications and a corresponding survival probability for silicon bipolar transistors as follows:

$$DM(K_D, MIN) = 2\pi f_{T(MIN)} \frac{1/h_{FE(FAIL)} - 1/h_{FE(MIN)}}{K \, \Phi \, SPEC} \quad \text{Eq. 50.1-4}$$

where

$f_{T(MIN)}$ is the manufacturer's specified minimum gain bandwidth product,

$h_{FE(MIN)}$ is the manufacturer's specified minimum current gain,

K is the universal silicon damage constant as obtained from Figure 4,

$h_{FE(FAIL)}$ is the current gain at which the circuit fails, and

ϕ_{SPEC} is the specified neutron fluence which the circuit under consideration must survive.

A standard deviation of 0.423 (references A-5 and A-6) may be taken as a worst-case estimate of the standard deviation in the logarithms of the universal silicon damage constant. In estimating part categorizaiton criteria, (PCC), from these data, an effective sample size of n = 53 should be used (see paragraph 5.1.6.2 in the main test and Appendix E). Then

$$PCC = e^{0.423} \times K_{TL}(n = 53, P, C,) \quad \text{Eq 50.1-5}$$

where P is the desired survival probability with confidence, C, and K_{TL} is the one-sided tolerance limit. For more information see reference A-6 and Appendix E. Table VI lists approximate PCC values for various failure probabilities, P_F (where P_D = 1-P). This table corresponds to 90 percent confidence that the failure probability is less than the listed value.

The damage effects discussed above hold true for times after which any short-term annealing has occurred. How short-term annealing takes place at different temperatures after exposure to neutron radiation for a 2N914 transistor is illustrated in Figure 5. For temperatures above about room temperature, for example, these curves show that the transistor has recovered to within about 10 percent of its long-term state in one second; at lower temperatures, this annealing process can take significantly longer. The dependence of short-term annealing on device characteristics and on neutron flux has been modeled recently (reference A-9).

TABLE VI. Transistor part categorizaton criteria for maximum probability of failure (P_F) at 90 percent confidence.*

P_F	PCC
10^{-1}	1.9
10^{-2}	3.1
10^{-3}	5.1
10^{-4}	6.8
10^{-5}	8.3
10^{-6}	11

* Calculated from the data of reference A-2 and the analysis of reference A-6.

50.2 Junction field-effect transistors. The construction of a dielectrically isolated N-channel planar-junction field-effect transistor is shown in figure 6 to assist the discussion of neutron damage effects in junction field-effect transistors (JFETs). In this type of device, reverse bias voltage V_G is applied to the gate, extending the gate-channel type of depletion layer into the channel region and modulating the effective depth of the conductive path between the source and the drain. The reverse bias which causes the depletion region to extend into the channel far enough to deplete the channel completely is defined as the pinch-off voltage, V_p.

At any given gate bias where $V_G < V_p$, an increase in drain voltage V_D will result in an increase in the drain-to-source current, I_{DS}. The ohmic voltage drop along the channel adds to the net bias across the gate-channel inter-face and causes the depletion region to extend further into the channel in the vicinity of the drain. Consequently, when $V_D \geq (V_p - V_G)$, the space charge region which is formed at the drain end of the channel causes I_{DS} to reach a saturation level and thus become insensitive to further increases in V_D.

the pinch-off voltage, Vp, is given by (reference A-10)

$$V_p = \frac{q\ N\ a^2}{2\epsilon} \qquad \text{Eq. 50.2-1}$$

and the transconductance, g_m, by the approximate expression, (reference A-11),

$$g_m \approx \frac{2a\ z}{L} \cdot q\mu N = \frac{1}{r_{d(on)}} \qquad \text{Eq. 50.2-2}$$

where $r_{d(on)}$ = slope of the I_{DS} - V_D curve at zero gate voltage (ohms),

μ = mobility (cm^2 /V·s),

z = channel width (cm),

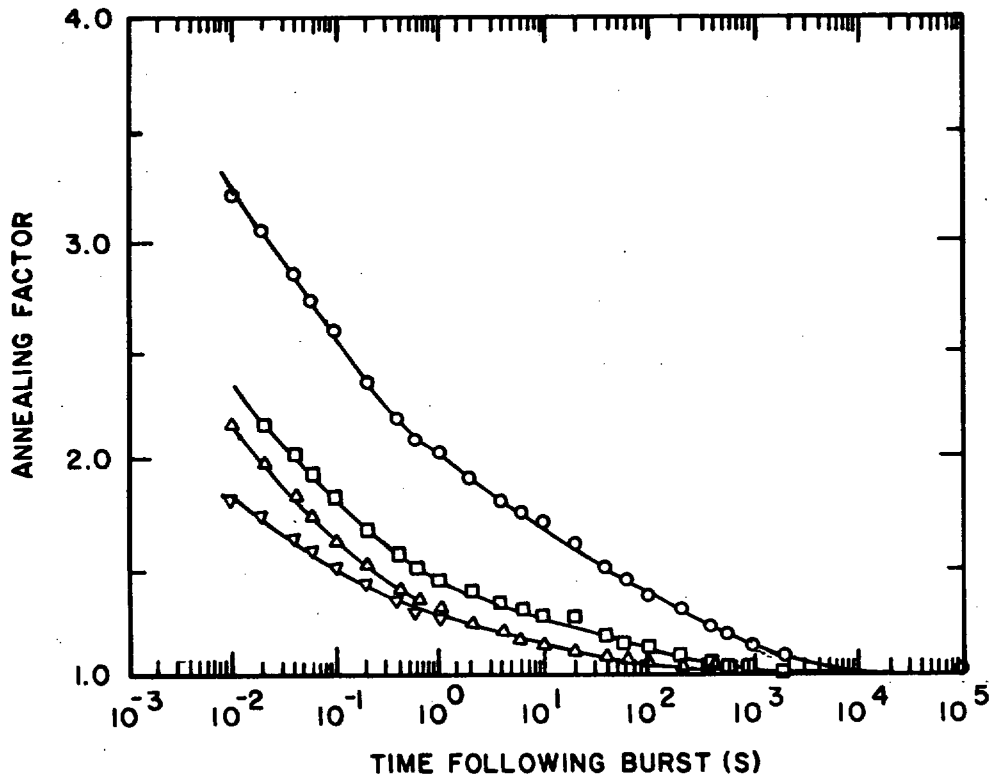

FIGURE 5. Annealing factor versus time after exposure to a neutron burst for a 2N914 transistor operating at a 2 mA peak collector current with a repetition rate of 100 Hz (2 μA average collector current) for temperatures: (○) 213 K, (□) 268 K, (△) 300 K, and (▽) 348 K. The annealing factor is defined as the ratio of the radiation-induced defect density at a given time to the density of stable defects which do not anneal. (REF. A-8).

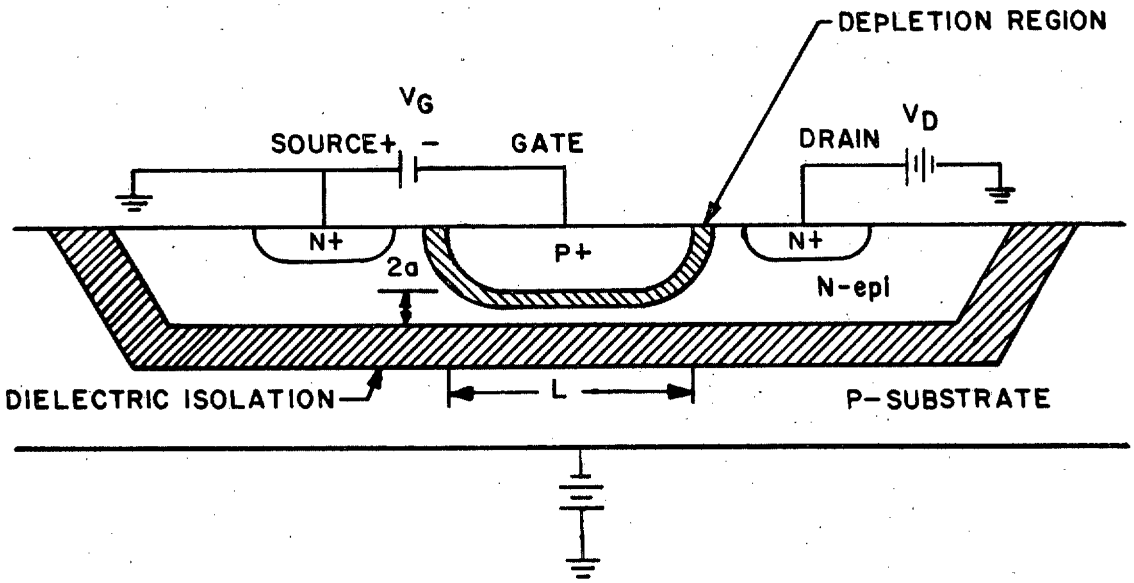

FIGURE 6. Cross section of a dielectrically-isolated n-channel junction field-effect transistor. The channel width extends a perpendicular distance z into the page.

2a = channel depth (cm),

L = channel length (cm),

N = majority carrier concentration in the channel (cm^{-3}),

q = electronic charge (C), and

ϵ = the permittivity (F/cm).

The parameter $r_{d(on)}$ gives a measure of the resistance of the channel. The drain-source saturation current, I_{DSS}, at zero-gate voltage is given approximately by

$$I_{DSS} \cong \frac{g_m V_p}{3} . \qquad \text{Eq. 50.2-3}$$

The most sensitive parameters to neutron damage are g_m, $r_{d(on)}$, I_{DSS}, and V_p. The neutron degradation of g_m is related to the neutron damage-induced changes in channel conductance and can be characterized by (reference A-10).

$$g_{m(rad)} = g_{mo} e^{-\frac{1}{K_J}\Phi} \qquad \text{Eq. 50.2-4}$$

where $g_{m(rad)}$ is the transconductance after radiation, g_{mo} is the transconductance before irradiation, and K_J has the experimentally determined values (to two significant figures) of $440(N)^{0.78}$ for an n-type channel and $390(N)^{0.78}$ for a p-type channel (reference A-12).*

Neutrons degrade JFETs by introducing traps which remove carriers in the channel region and by reducing mobility. These effects lead to observed lower values for I_{DSS} and V_p. In JFETs with dopant levels above 10^{15} cm^{-3}, fluences of less than 10^{13} n/cm^2 cause less than a 1 percent change in the carrier concentration. N-channel JFETs having heavily doped channels (>3 x 10^{16} cm^{-3}) will undergo a 50 percent degradation in the source-drain current at a fluence of about 2 x 10^{15} n/cm^2 (reference A-11). More lightly doped channels will degrade at lower fluences. Data on neutron-induced damage for P-channel JFETs are less plentiful, but there is some evidence that they are slightly less sensitive than N-channel devices.

The drain-source saturation current, I_{DSS}, at zero source-gate voltage decreases more rapidly with neutron radiation than g_m. In turn, g_m decreases more rapidly than Vp. Calculated and experimental decreases of these three parameters with neutron fluence lead to the selection of I_{DSS} as the most sensitive electrical parameter for neutron effects. However, several hardness assurance screening parameters were examined in one study (reference A-14), where $r_{d(on)}$ was selected as the most appropriate parameter.

A threshold neutron fluence, ϕ_{TH}, below which JFETs will not be significantly affected, can be calculated from a typical lower bound value of channel doping found in JFETs (10^{15} cm^{-3}). On the basis of Eq. 50.2-4 and an assumption that a change of less than 10 percent in g_m is not signficant,

$$\Phi_{TH} = -K_j \ln \frac{g_{m(rad)}}{g_{mo}}$$

$$= -440 \times (10^{15})^{0.78} \ln 0.9$$

$$= 2.3 \times 10^{13} \text{ n/cm}^2.$$

*Another set of experimental data (reference A-13) gives values of $31.8(N)^{0.875}$ and $41.8(N)^{0.858}$ for n- and p-type silicon, respectively.

APPENDIX A

References

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APPENDIX B

REFERENCE DIODE HARDNESS ASSURANCE

10. GENERAL

10.1 Scope. This appendix details the effects of neutron radiation on reference diodes.

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. DETAIL EXAMPLE

50.1 Effects of neutron radiation. Voltage reference diodes are PN junction devices operated in the reverse direction with sufficient bias to cause avalanche or Zener breakdown. The desired properties of a voltage reference diode are that very little current should exist at bias levels less than the specified breakdown voltage, while at breakdown the Zener or avalanche process should hold the voltage drop across the diode constant over many decades of current.

For avalanche diodes, the breakdown voltage is a function of the doping levels (and other parameters) and increases with neutron irradiation. For voltage reference diodes rated for use above 7 to 8 V, avalanche breakdown is the dominant process.

Zener breakdown is electrically similar to avalanche breakdown except that the breakdown results from band-to-band tunneling. In this mechanism, electrons tunnel from the valence band of the heavily doped P region across the thin junction to the conductance band of the heavily doped N region. Where Zener breakdown is the dominant process, diodes exhibit relatively low breakdown voltages (less than about 6 V) and a breakdown characteristic less abrupt than avalanche diodes. Voltage reference diodes based on Zener breakdown show a decrease in the breakdown voltage with neutron irradiation.

The high doping levels in all such simple reference diodes make them inherently radiation resistant. Typically, for a simple silicon reference diode, a one percent change in the breakdown voltage is not reached until neutron fluences exceed 1 x 10^{14} n/cm^2 (reference B-1).

Temperature compensated reference diodes, however, are sensitive to radiation (reference B-2). To provide temperature compensation, one or more forward-biased diodes are added in series to the simple reverse-biased biased reference diode. (Because most temperature compensated reference diodes utilize avalanche breakdown, this mechanism will be assumed in the remainder of the appendix.) The negative temperature coefficient of the forward-biased PN junction voltage is used to compensate for the positive temperature coefficient of the reverse-biased junction voltage. The forward-biased characteristics of a diode is more sensitive to neutron damage effects than the reverse-biased characteristic. For this reason, it is important to deal with the response of forward-biased diodes to neutron irradiation in discussing temperature compensated reference diodes.

The forward voltage of a diode with a heavily doped N region is given approximately by

$$V \approx \frac{nkT}{q} \ln \frac{I_D\sqrt{\tau_n}}{n_p q A \sqrt{D_n}} \qquad \text{Eq. 50.1-1}$$

where τ_n is the minority carrier lifetime in P-type material (s),

A is the junction cross-sectional area (cm^2),
q is the electronic charge (C),
D_n is the diffusion constant for electrons in P-type material (cm^2/s),
n_p is the number of minority carriers in the P-region (cm^{-3}),
I_D is the forward diffusion current (A), and
n is an empirical constant between 1 and 2.

The effect of neutron radiation on minority carrier lifetime is given by

$$\frac{1}{\tau_\Phi} = \frac{1}{\tau_0} + \frac{\Phi}{K_\tau} \qquad \text{Eq. 50.1-2}$$

where τ_Φ is the minority carrier lifetime after exposure (s),
τ_0 is the initial minority carrier lifetime (s),
K_τ is the lifetime damage constant ($n\cdot s/cm^2$), and
Φ is the total fast neutron fluence (n/cm^2).

Under the assumption that the lifetime degradation in the forward diode dominates all other damage mechanisms in the reference diode, the change in forward voltage with neutron radiation can be obtained from Eqs. 50.1-1 and 50.1-2:

$$\Delta V = V_0 - V_\Phi = \frac{nkT}{2q} \ln (1 + \tau_0 K \Phi), \qquad \text{Eq. 50.1-3}$$

where V_0 and V_Φ are the forward voltages before and after irradiation, respectively, and K_τ has been replaced by the universal silicon damage constant, K, whose value at a particular current density is obtained from figure 4. This equation can be rearranged as follows to give a convenient form for calculating the fluence which can be tolerated in a given situation:

$$\Phi = \left(e^{\frac{2q\Delta V}{nkT}} - 1 \right) / \tau_0 K . \qquad \text{Eq. 50.1-4}$$

For example, a 1-mV change in the forward voltge drop in a diode having an initial lifetime of 10^{-6} s will result from a neutron fluence of about 10^{11} n/cm^2, given that kT/q is 26 mV at room temperature, $n \approx 1$, and K is of the order of 10^{-6} $cm^2/n\cdot s$. Note that for temperature compensated reference diodes with more than one forward-biased junction, the ΔV of the device will be proportional to the number of forward-biased junctions it has.

Wide variations in the sensitivity of reference diodes to neutron radiation have been found. Even for a single type, the 1N829, recent data have shown (reference B-2) changes in voltage drop ranging from 0.53 to 28.9 mV at a fluence of $10^{12} n/cm^2$ and from 4.44 to 67.2 mV at 10^{13} n/cm^2. Diodes from a single manufacturer, date coded eight weeks apart, differed by a factor of twelve in their voltage change at these fluences. The source of these variations was shown to be a function of the lifetime and the number of forward-biased compensating diodes. Hence, for moderate neutron environments ($\Phi < 10^{13}$ n/cm^2), the lifetime and the number of forward diodes used for temperature compensation should be controlled.

An electrical screen on lifetime would be effective for hardness assurance if lifetime could be determined from switching time measurements. Unfortunately, the back-to-back structure of the temperature compensated reference diode makes switching time measurements ambiquous. Because of wide variations in the neutron response of temperature compensated reference diodes and the lack of adquate electrical screens, radiation sample testing by production lot or diffusion lot may be necessary.

APPENDIX B

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APPENDIX C

TRANSISTOR-TRANSISTOR HARDNESS ASSURANCE

10. GENERAL

10.1 Scope. This appendix details the effects of neutron radiation on transistor-transistor logic.

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. DETAIL EXAMPLE

50.1 Effects of neutron radiation. Satisfactory performance of transistor-transistor logic, TTL, depends on the driving capability of the output transistors Q3 and Q4 in the TTL gate shown in figure 7. As the gain, h_{FE}, of the output transistors decreases because of displacement damage produced by neutron irradiation, so does the output current of the TTL gate. The major effect of the damage is a reduction in the low-level output current, I_{OL}, and a consequent reduction of the fan-out capability of the circuit. The primary parameter in determining I_{OL} is the h_{FE} of the output transistor Q3. The I_{OL} of the output transistor is approximately proportional to h_{FE} (reference C-1). Knowledge of the h_{FE} degradation characteristics of the output transistor Q3 therefore provides a means for predicting TTL gate performance, particularly under high fan-out conditions.

The unsaturated output sink current, I_{SK}, is related to the h_{FE} of transistor Q3 and can be measured directly with the output of the gate in the low state by forcing sufficient current into the output of the device to drive transistor Q3 out of saturation (reference C-2). I_{SK} is therefore limited by the h_{FE} of Q3. Since the base current, I_B, of transistor Q3 depends primarily on the value of resistor R_2 and to a lesser degree on V_{BE} and $V_{CE(SAT)}$ of the internal transistors, I_B is essentially constant. Thus, the measurement of I_{SK} may be used to determine the device damage factor of the output transistor. Although this approach has several limitations, fortunately they are of second-order importance. These limitations are: (1) circuit variations in V_{BE} and $V_{CE(SAT)}$ are not included, (2) resistor values depend on process variations, and (3) h_{FE} is measured at a fixed I_B. Because I_{SK} is measured under conditions of constant I_B, the collector current, I_C, can vary between units because of the variability of h_{FE}. Although this variation is not great, it can lead to difficulty because of the dependence of h_{FE} and the device damage factor, K_D, on I_C. This difficulty can be reduced by measuring I_{SK} at a lower collector supply voltage, V_{CC}, so that the collector current density is below the point where h_{FE} is a maximum (reference C-3).

The h_{FE} of transistor Q3 is given by

$$h_{FE} = \frac{I_{SK}}{I_B} \qquad \text{Eq. 50.1-1}$$

where I_B is determined by circuit analysis to be

$$I_B \cong \frac{V_{CC} - 3V_{BE}}{R1} + \frac{V_{CC} - V_{CE(SAT)Q2} - V_{BE}}{R2} - \frac{V_{BE}}{R3}. \qquad \text{Eq. 50.1-2}$$

If sufficient data on I_{SK} were available for lot-to-lot and manufacturer-to-manufacturer variations for each of the TTL families, the data could be converted to K_D and statistically characterized. If the variations in electrical parameters of the constituent transistors were known, a transistor worst-case model (reference C-4) could be used to calculate an upper bound for K_D. In the absence of such

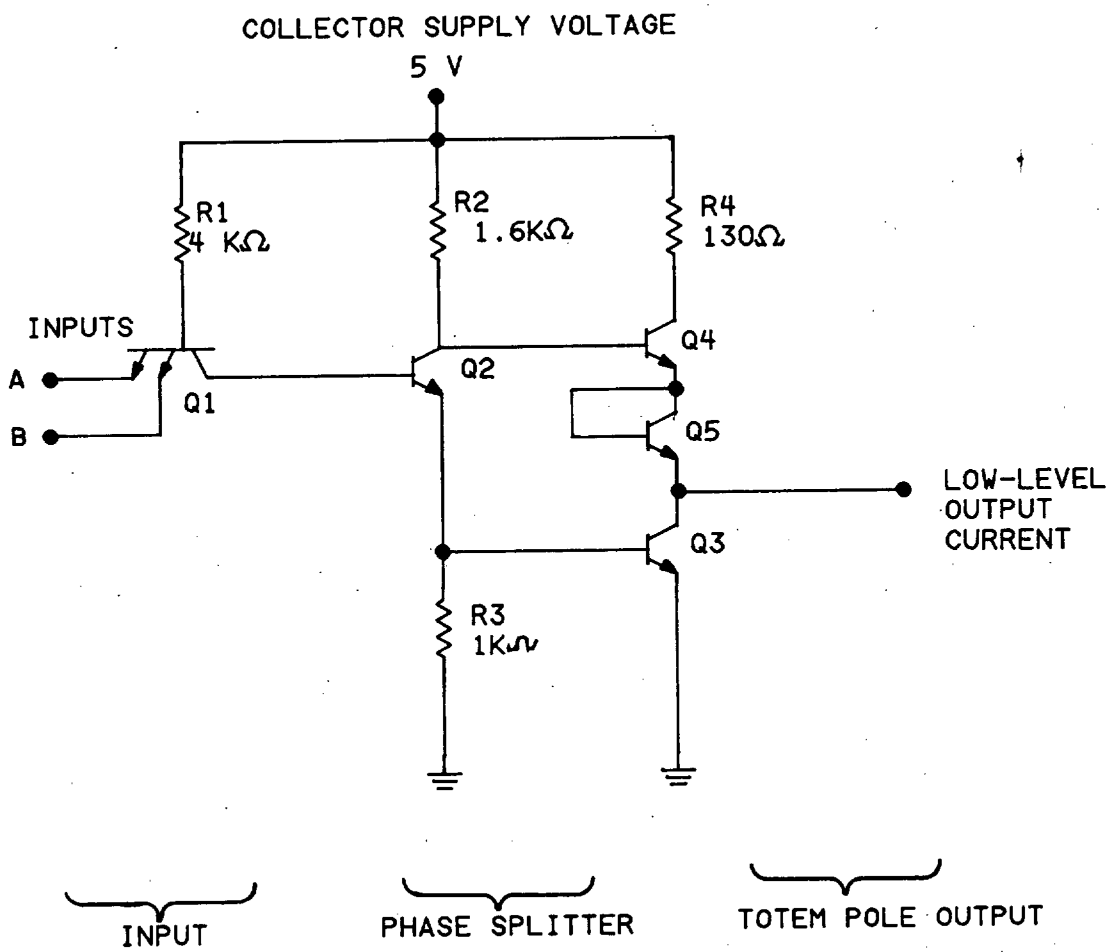

FIGURE 7. Circuit diagram for a SN5400 transistor-transistor logic gate.

information, it is assumed that the variations encounted in TTL devices will be no greater than those encountered in discrete transistors.

For TTL devices, the worst-case condition corresponds to the maximum specified fan-out. As the fan-out decreases, the forced gain, h_{FEF}, decreases because it is directly proportional to collector current. In othe words, if the fan-out drops from 10 to 5 (a factor of 2), the fluence to failure for the standard TTL family increases by a fctor of 2. This rule-of-thumb must be applied with some caution (especially in the case of flip flops) because it is possible for an internal transistor to fail before the output transistor fails.

Assuming a constant $I_{B(MIN)}$, which is calculated from circuit analysis of the output TTL gate stage, a worst-case design margin $DM(K_D, MIN)$, similar to that given in Appendix A (Eq. 50.1-4) may be obtained as

$$DM(K_D, MIN) = 2\pi f_{T(MIN)} I_{B(MIN)} \frac{1/I_{SK(FAIL)} - 1/I_{SK(MIN)}}{K\phi_{SPEC}} \qquad \text{Eq. 50.1-3}$$

where $f_{T(MIN)}$, K, and ϕ_{SPEC} are defined in Eq. 50.1-4 of Appendix A, $I_{B(MIN)}$ and $I_{SK(MIN)}$ are the manufacturer's specified minimum values for I_B and I_{SK}, and $I_{SK(FAIL)}$ is the value of I_{SK} at which the circuit fails. For part categorization purposes, this design margin is to be compared with the PCC values calculated from Eq. 50.1-5. This criterion applies to TTL devices for which it is assumed that the device will fail because of the failure of the output transistor rather than to failure of an internal transistor. Such failure is more likely to be true for the large fan-out case than it is for the small fan-out case because the output transistor safety margin is lower for high fan-out. Unless a better estimate is available, $f_{T(MIN)}$ can be replaced by 250 x 10^6 Hz for SSI TTL devices, and I_{SK} by the values below (depending on the fan-out).

Estimated $I_{SK(FAIL)}$	Fan-Out
35 mA	10
12 mA	5
5 mA	2
2.5 mA	1

Several hardness assurance electrical parameters have been proposed for TTL circuits, but limitations exist for all of them as can be seen in Table VII. Of the candidate parameters listed in this table, I_{SK} appears to be the best.

Johnston and Skavland (reference C-3) propose an electrical measurement technique that makes use of the difference between the power supply voltage, V_{CC}, and the output high voltage, V_{OH}, with modified input conditions to provide an effective test parameter for the neutron response of TTL ICs. This technique requires that the chip circuit design and internal transistor geometry be known and fixed.

Changes in switching times of TTL devices after neutron exposure can also be related to transistor h_{FE} degradation. However, the relationship between h_{FE} and switching time is strongly nonlinear with neutron fluence. The propagation delay time, t_{PLH}, is defined as the time between the specified reference points in the input and output voltage waveforms with the output changing from a defined low level to a defined high level. The propagation delay time, t_{PHL}, is a similarly defined quantity with the output changing from a defined high level to a defined low level. An estimate of the f_T of th phase splitter and output transistors can be obtained from these propagation delay times. In practice, low correlation has been found between neutron damage and propagation delay (reference C-3 and C-6), so the effectiveness of this approach for a hardness assurance test is reduced.

TABLE VII. Transistor-transistor logic hardness assurance and quality conformance parameters.

Parameter	Advantages	Limitations
I_{SK} (output sink current)	1. Gain margin of output transistor can be established. 2. I_{SK} is easily measured. 3. I_{SK} degrades in a manner similar to h_{FE} of individual transistor. 4. A standard measurement method is available (reference C-2).	1. V_{BE} and $V_{CE(SAT)}$ variations in circuit not included. 2. Gain measured at fixed base current (collector current will vary). 3. Process-induced variations of resistors not included.
V_{OH} (output high voltage)	1. A dc measurement. 2. Applicable to most TTL devices. 3. No special metallization pattern required.	1. Circuit design needs to be fixed. 2. Transistor geometries need to be fixed. 3. Leakage currents not included.
t_{PLH} and t_{PHL} (propagation delay time for low to high and for high to low)	1. f_T of the phase-splitter and output transistors can be estimated. 2. Useful for more complex circuits.	1. Switching time tends dominated by output load capacitance. 2. f_T measurements are not easily made. 3. Requires special metallization pattern.
V_{OL} (output low voltage)		1. Changes in this parameter are small, so measurements must be very accurate.

Another approach to assure radiation hardness involves the use of devices with special built-in leads which allow direct access to the base of the output transistor (reference C-7). However, variations in transistor parameters across a wafer may be severe enough so that the characteristics of the output transistor may not accurately predict the worst-case element degradation for devices more complex than small-scale integration ICs. Specialized test transistors should be selected such that they are representative of the lowest gain-bandwidth product and the largest area of any transistor in the circuit itself.

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APPENDIX D

OPERATIONAL AMPLIFIER HARDNESS ASSURANCE

10. GENERAL

10.1 Scope. This appendix details the effect of neutron radiation on operational amplifiers.

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

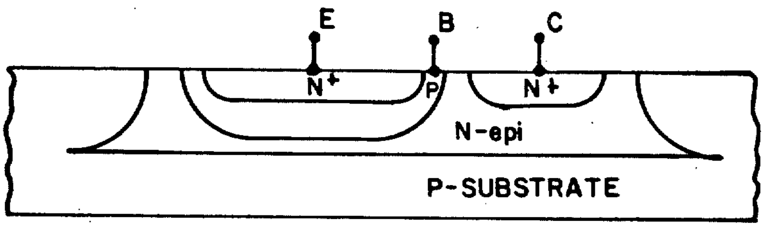
50. DETAIL EXAMPLE

50.1 Effects of neutron radiation. Hardness assurance methods for operational amplifiers must consider not only the device damage factors of the component transistors but the effect of internal circuit design on the radiation response. The specific design techniques used in linear circuits affect internal design margins and depend on matching the base-emitter voltage versus collector current characteristics as well as the gains of transistors. Because most linear devices will fail catastrophically at sufficiently high neutron levels, hardness assurance methods must also deal with the potential of a catastrophic failure as well as the more gradual changes in electrical parameters that occur at the lower fluences.

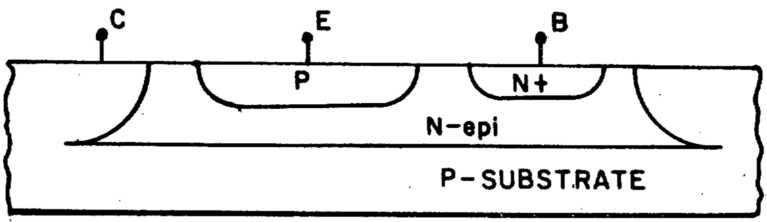
Four general types of transistors can be encountered in bipolar operational amplifier designs*: (1) typical NPN transistors, (2) super-gain NPN transistors, (3) lateral PNP transistors, and (4) vertical (substrate) PNP transistors (reference D-1). The sensitivities of these different devices to neutron damage vary widely because of differences in geometry, doping levels, and base width. Table VIII lists their typical electrical parameters, and figure 8 compares the structure of the two PNP devices with the standard NPN transistor. Table IX shows the types of transistors used in the design of several representative operational amplifiers.

The two PNP transistor types are compromise designs that can be fabricated without additional process steps. Both have wide base regions and so have lower f_T values and higher device damage factors than the NPN transistors. Thus, any part of a linear circuit that uses PNP transistors will be more sensitive to neutron damage unless the part of the circuit can tolerate very low transistor gain. For example, lateral PNP transistors are frequently used as current repeaters or mirrors (reference D-4) which depend on α (the common base gain) and can tolerate very low gain values. On the other hand, transistor Q_{17} in the 741 operational amplifier shown in figure 9 is a substrate PNP transistor that sinks current in the push-pull output stage. The sink current is limited by the gain of this transistor.

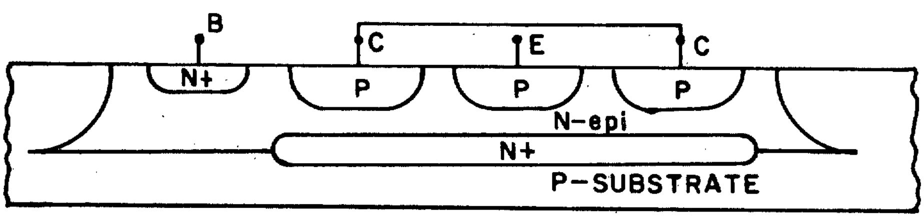
* It is also possible to fabricate high f_T PNP transistors with dielectrically isolated processes. However, this appendix is limited to the junction-isolated devices used in standard commercial processes.



(a) Typical NPN IC transistor.



(b) Vertical (Substrate) PNP transistor.



(c) Lateral PNP transistor.

FIGURE 8. Schematic cross sections of (a) a typical NPN integrated circuit transistor, (b) a vertical (substrate) PNP transistor, and (c) a lateral PNP transistor. (REF. D-3)

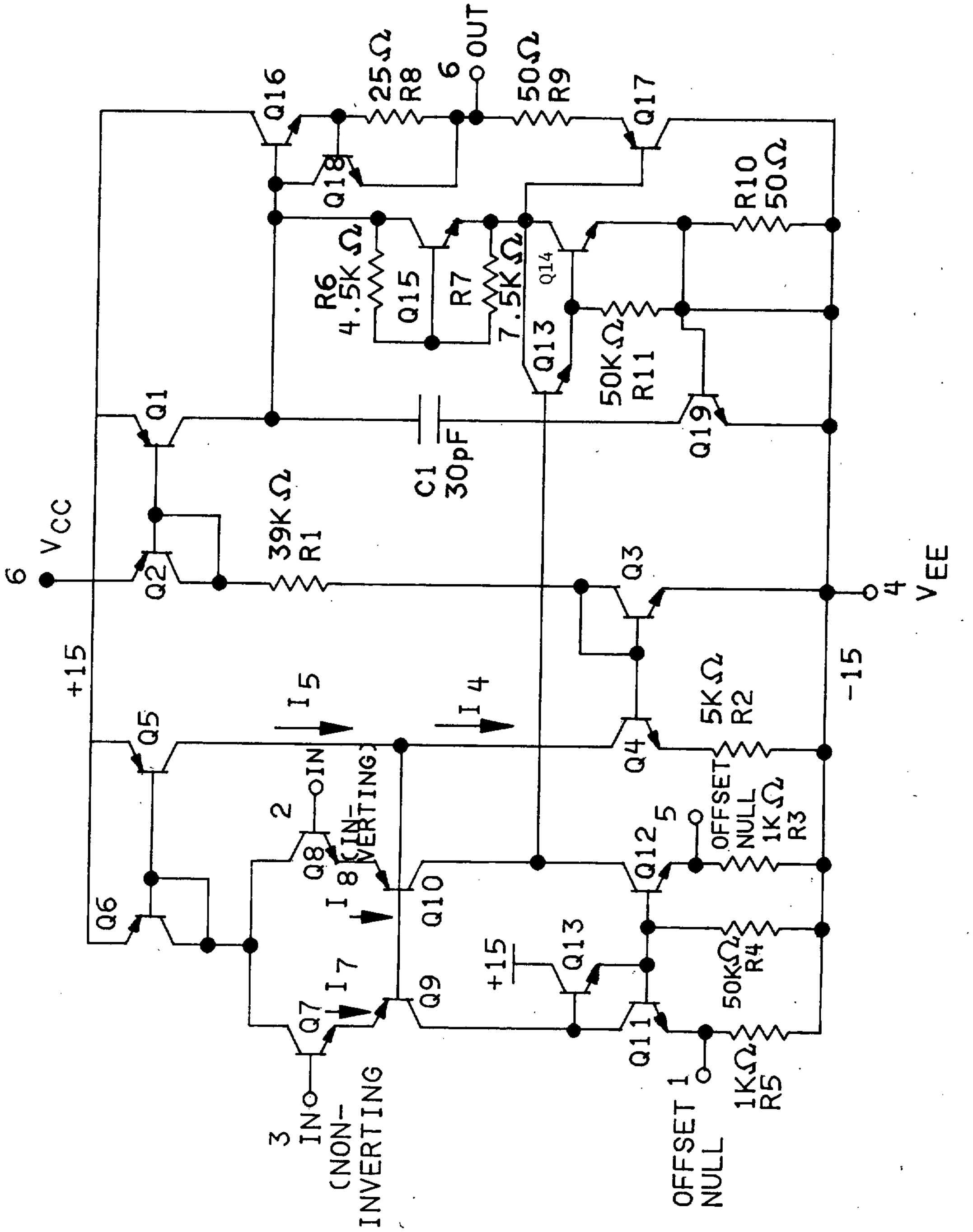


FIGURE 9. Circuit diagram of a 741 operational amplifier.

TABLE VIII. Typical electrical parameters of transistor structures used in linear integrated circuits (reference D-2).

Transistor type	Gain AT I_C	Gain - Bandwidth product MHz	Breakdown voltage V
Standard NPN	200 - 300 10 μA	400	60
Super-Gain NPN	2000 - 3000 10 μA	600	2 - 6
Lateral PNP	40 - 100 100 μA	2	55
Substrate PNP	100 - 150 100 μA	10	90

TABLE IX. Types of transistors used in selected operational amplifiers (reference D-2).

Circuit type	Internal component types			
	NPN	Super-gain NPN	Lateral PNP	Substrate PNP
101A	X		X	
108A	X	X	X	X
741	X		X	X
124	X		X	X

The operational amplifier parameters that show the most significant changes after neutron irradiation are the input offset voltage (V_{OS}), input bias current (I_B), input offset current (I_{OS}), open-loop voltage gain (A_{VOL}), output sink and source current, and slew rate (S_R). Other parameters such as power supply current, common-mode rejection ratio, power supply rejection ratio, and bandwidth usually do not change substantially until the more sensitive parameters have degraded severely.

Before hardness assurance can be implemented for a specified device, the failure modes of the circuit must be established. This procedure requires a combination of circuit analysis and radiation test data. Catastrophic failure modes are usually associated with PNP transistors becuase of their large device damage factors. For the 741 operational amplifier as an example, the test data in Table X show the sensitivity of various parameters. The parameters that show the largest changes are the input bias current and the open-loop voltage gain. Catastrophic failure can occur in the 741 operational amplifier when the lateral PNP current sources can no longer supply the current to bias internal circuitry, or when the substrate PNP transistor in the output stage degrades sufficiently. The first mechanism depends on α, not h_{FE}, and can tolerate relatively low gain values. The second mechanism is therefore the most likely to occur. However, the data in the test sample shown in Table X show that the output sink current was still adequate, after the highest fluence level, to meet the device specifications. The series resistor (R9) prevents measurement of the gain-limited current until it falls below the saturated limit of 25 mA, masking the sensitivity of Q_{17} to neutron damage, (except for particular units with low initial gain values). The second failure mechanism is still an important one to consider even though it did not occur for this small test sample (reference D-2).

TABLE X. Neutron degradation of typical parameters of the 741 operational amplifier (reference D-5).

S/N	Parameter	Neutron fluence (n/cm^2)			
		Pretest	2.26×10^{12}	4.92×10^{12}	9.6×10^{12}
2 3 4	V_{OS} mV	- 0.76 - 2.26 0.36	- 0.80 - 2.36 0.41	- 1.03 - 2.53 - 1.42	- 1.48 - 3.10 - 4.24
2 3 4	I_B nA	11.4 21.0 53.9	48.1 70.0 159.5	77.1 105 262	163 220 469
2 3 4	I_{OS} nA	0.61 2.08 4.65	- 2.65 3.41 9.20	- 8.8 4.35 8.1	- 9.5 - 6.8 4.9
2 3 4	Slew Rate V/μs	0.92 0.97 1.04	0.92 0.98 0.97	0.87 0.94 0.88	0.78 0.85 0.75
2 3 4	Open Loop Gain	251 K 265 K 486 K	333 K 248 K 88.6 K	268 K 189 K 23.9 K	48.9 K 38.4 K 10.1 K

50.2 Electrical parameter tests. Changes in I_B are important in most operational amplifier applications. Since I_B is very sensitive to radiation, it is a good indicator of the onset of significant damage in the input transistors. However, the behavior of I_B may give a misleading picture of the circuit performance if NPN transistors are used at the inputs, because they have much higher f_T's (and lower device damage factors) than the internal PNP transistors. For low neutron fluences ($\leq 10^{12}$ n/cm^2), the change in I_B with fluence is approximately linear because I_B is the input transistor base current. For the simplified equivalent operational amplifier circuit of figure 10 (reference D-6), we have:

$$I_B = \frac{I_{B1} + I_{B2}}{2} \qquad \text{Eq. 50.2-1}$$

$$I_T \cong I_{C1} + I_{C2} \qquad \text{Eq. 50.2-2}$$

$$1/h_{FE1} = \frac{I_{B1}}{I_{C1}} \qquad \text{Eq. 50.2-3}$$

$$\Phi K_{D1} = 1/h_{FE1(rad)} - 1/h_{FE1(0)} \qquad \text{Eq. 50.2-4}$$

$$\Phi K_{D2} = 1/h_{FE2(rad)} - 1/h_{FE2(0)} \qquad \text{Eq. 50.2-5}$$

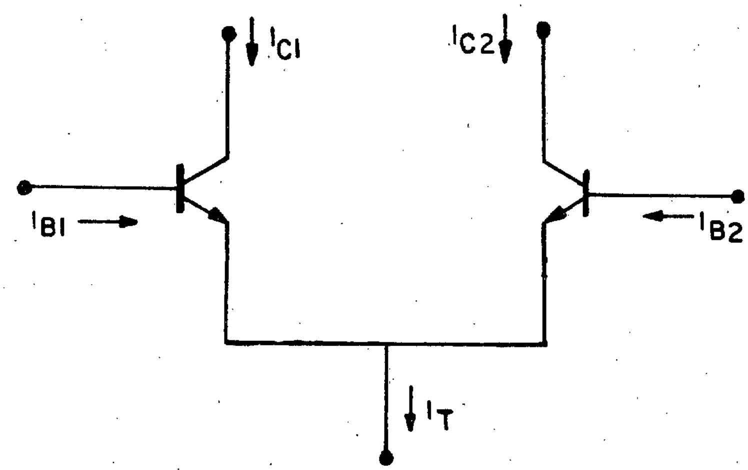


FIGURE 10. Equivalent circuit for an operational amplifier differential input stage.

If Eqs. 50.2-4 and 50.2-5 are added and Eq. 50.2-3 is used,

$$\Phi(K_{D1} + K_{D2}) = \frac{I_{B1(rad)}}{I_{C1(rad)}} + \frac{I_{B2(rad)}}{I_{C2(rad)}} - \frac{I_{B1(0)}}{I_{C1(0)}} - \frac{I_{B2(0)}}{I_{C2(0)}} . \qquad \text{Eq. 50.2-6}$$

If it is assumed that the first stage is balanced so that $I_{C1} \approx I_{C2}$ and if $k_D = (K_{D1} + K_{D2})/2$, then

$$\Phi K_D = \frac{2I_{B(rad)}}{I_{T(rad)}} - \frac{2I_{B(0)}}{I_{T(0)}} . \qquad \text{Eq. 50.2-7}$$

The first stage current, I_T, degrades with neutron damage, and this must be taken into account in order to determine the input transistor damage factor. I_T can be measured directly at the compensation terminal for most externally compensated operational amplifiers. For internally compensated units, such as the 741, the measurement cannot be made on the standard package. Either I_T can be estimated from the slew rate (reference D-5), becuase it is approximately proportional to I_T, or a special lead must be brought out to the unused pin 8 on the package. The input stage current of the 741, I_7 plus I_8 in figure 9 is derived from the collector of Q6. The Q5 collector current (I_5 in figure 9) also is equal to $I_7 + I_8$ which in turn is approximately equal to I_4, the stabilized current. Thus, any point which allows the monitoring of $I_7 + I_8$ can be brought out to pin 8 for hardness assurance monitoring.

The slew rate in a 741 operational amplifier is proportional to the gain of the lateral PNP transistors Q_1 and Q_2 which form a current mirror. This proportionality holds if it is assumed that the gains of the NPN transistors are very much greater than the gains of the lateral PNP transistors. The radiation-induced change in slew rate then depends on the current mirror, which can be related to the gain of the lateral PNP by the equation (references D-2 and D-4).

$$\frac{S_{R(rad)}}{S_{R(0)}} = \frac{\dfrac{1}{1 + 2/h_{FE(rad)}}}{\dfrac{1}{1 + 2/h_{FE(0)}}} = \frac{h_{FE(0)} + 2}{h_{FE(rad)} + 2} \cdot \frac{h_{FE(rad)}}{h_{FE(0)}} . \qquad \text{Eq. 50.2-8}$$

The open-loop gain degrades with neutron fluence but it does not change in an easily predictable way. For the 741 operational amplifier, the gain depends on the high impedance of the lateral PNP current source loads and also on the loading of the first stage by the Darlington transistor pair Q_{13} and Q_{14}. The data in Table X show a correlation between the input bias current and the open-loop gain, indicating that the NPN gain is the most significant contribution to the open-loop gain loss.

In addition, the measurement of the open-loop gain is not straightforward. The open-loop voltage gain must be correctly defined and carefully measured to permit a meaningful interpretation of the degradation of this parameter in a radiation environment. The best approach is to measure the transfer characteristic in both loaded and unloaded conditions and define the gain in terms of the maximum input voltage required to drive the output voltage through a given range. The reason for this is that many manufacturers specify a dc measurement for A_{VOL}, forcing the output from a negative to a positive voltage with a fixed load-resistor. However, Johnston (reference D-5) describes some problems with this procedure which make it difficult to use:

a. Most modern operational amplifiers have a 3-dB corner frequency in the 1 to 10 Hz region before irradiation. It is thus important that the test time be sufficiently long to establish equilibrium.

b. The output stage has a significant effect on the open-loop gain. The gain is a function of the load conditions and changes substantially between loaded and unloaded conditions. The gain in the loaded condition is a function of the signal amplitude.

Johnston (reference D-5) has suggested measurement of the first stage current, I_T (see figure 10), as a means of identifying operational amplifiers which may fail at abnormally low neutron fluences. The input bias current is the base current of the bipolar transistor differential stage. It may be shown from Eq. 50.2-7 that

$$\frac{\Delta I_B}{I_T} \approx \frac{K_D \phi}{2}$$

For operational amplifiers with equal damage factors, K_D, ΔI_B will be directly proportional to I_T. Hence, the use of a qualification test to remove operational amplifiers with the higher values of I_T will result in reducing the radiation-induced change in the input bias current that may be expected. The removal of undesirable devices may be accomplished by placing a maximum limit on the slew rate because it is proportional to I_T (reference D-5).

The hardness assurance approach measures the degradation of internal transistors using standard circuit parameters that can be analytically related to such degradation. In order to minimize the possibility of catastrophic failure, use of operational amplifiers should be restricted to levels well below those at which operational failure occurs for small test samples. The safety margin selected should be based on test data and analysis of the potential catastrophic failure mechanisms.

APPENDIX D

References:

D-1. A. H. Johnston, Hand Analysis Techniques for Neutron Degradation of Operational Amplifiers, IEEE Trans. Nucl. Sci. NS-23, 1709 (December 1976).

D-2. A. Johnston, personal communication.

D-3. D. J. Hamilton and W. G. Howard, Basic Integrated Circuit Engineering, McGraw-Hill, 1975.

D-4. J. Millman, Microelectronics: Digital and Analog Circuits and Systems, McGraw-Hill Book Co., 1979, p. 538.

D-5. A. H. Johnston, Application of Operational Amplifiers to Hardened Systems, IEEE Trans. Nucl. Sci. NS-24, 2701 (December 1977).

D-6. G. C. Messenger, personal communication.

APPENDIX E

STATISTICAL TECHNIQUES FOR HARDNESS ASSURANCE

10. GENERAL

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

20. REFERENCED DOCUMENTS

Not applicable.

30. DEFINITIONS

Not applicable.

40. GENERAL REQUIREMENTS

Not applicable.

50. STATISTICAL TECHNIQUES

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

a. Reference E-1 for basic concepts

b. Reference E-2 for industrial quality control

c. Reference E-3 for statistical techniques in data analysis

d. Reference E-4 for a complete guide to statistical analysis

e. References E-5 and E-6 for the statistics of sampling and quality control

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

$p_i \equiv$ Probability that the i'th possibility will occur. Eq. 50.1-1

Obviously,

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

It is also customary in standard texts to use q_i for the probability that the i'th possiblity will not occur.

$$q_i = 1 - p_i. \qquad \text{Eq. 50. 1-3}$$

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

$P_S \equiv$ Probability that a part will survive and, Eq. 50.1-4

$P_F \equiv$ Probaiblity that a part will fail Eq. 50.1-5

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

50.1.2.1 The probability distribution function - pdf. The probability distribution function (often referred to as pdf) gives the probability that a randomly distributed value x will be between the limits x and x + dx, where dx is an infinitesimal increment. This is illustrated in figure 11.

$$f(x)dx = \text{Probability that } x \text{ is between } x \text{ and } x+dx \qquad \text{Eq. 50.1-6}$$

50.1.2.2 The cumulative distribution function - cdf. The cumulative distribution function (often referred to as cdf) is the probability that the variable x will be less than the value X.

$$F(X) \equiv \text{Probability that } x \leq X = \int_{-\infty}^{X} f(x)\, dx \qquad \text{Eq. 50. 1-7}$$

The meaning of F(X) is illustrated in figure 12

50.1.3 Means and standard deviations. Every probability distribution is characterized by a mean, μ, and a standard deviation, σ. The variance is simply the square of the standard deviations σ^2.

50.1.3.1 Discrete distributions. For discrete distributions where the different possibilites refer to numerical values, x_i, and where there are N possibilities,

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

and

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

which is equivalent to

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

50.1.3.2 Continuous distributions. The means and variances for continuous distributions are given by

$$\mu = \int_{-\infty}^{\infty} X\, f(x)\, dx \qquad \text{Eq. 50. 1-10}$$

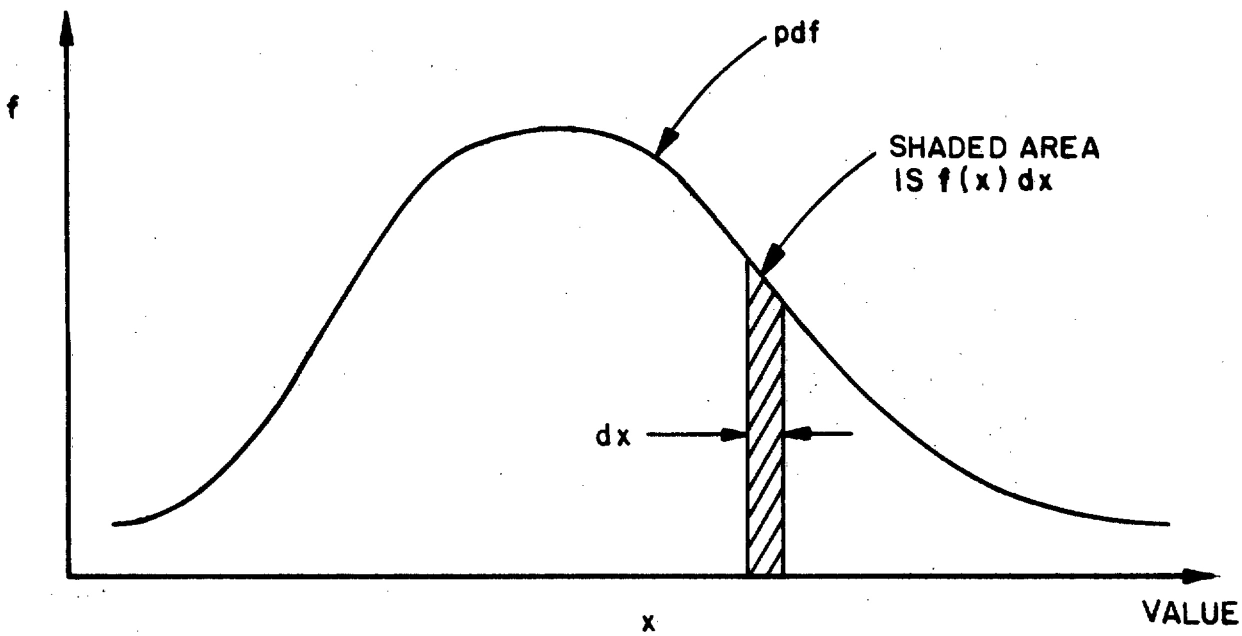


FIGURE 11. Probability distribution function.

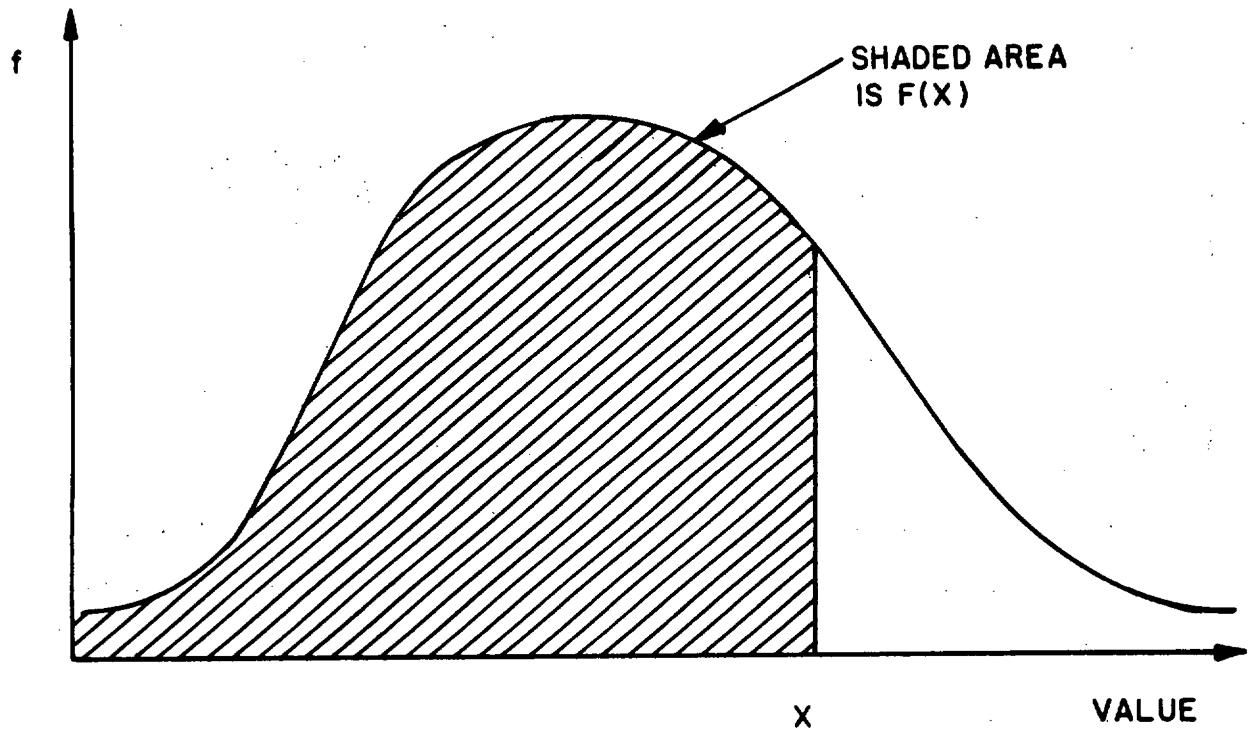


FIGURE 12. Cumulative distribution function.

and

$$\sigma^2 = \int_{-\infty}^{\infty} (x - \mu)^2 f(x)\, dx \qquad \text{Eq. 50. 1-11a}$$

which is equivalent to

$$\sigma^2 = \int_{-\infty}^{\infty} x^2 f(x)\, dx - \mu^2 \qquad \text{Eq. 50. 1-11b}$$

50.1.3.3 Means and standard deviations for a measurement. When the outcome of an experiment is a numerical value and when N items have been sampled from either a discrete or a continuous distribution, these N values give measured estimates of the true mean and standard deviation. These estimates are denoted by the symbols m and S respectively.

$$m = \frac{1}{N} \sum_{i=1}^{N} x_i \qquad \text{Eq. 50. 1-12}$$

$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - m)^2 \qquad \text{Eq. 50. 1-13a}$$

or

$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} x_i^{\,2} - Nm^2 \qquad \text{Eq. 50. 1-13b}$$

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

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

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

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

50.2.1.1 Standard normal distributions. By a linear transformation of variables, any normal distribution may be expressed as a normal distribution with a mean of zero and a standard deviation of unity. The probability distributions after a sufficiently large number of steps have been made.

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

$$f_n\,(x) = \frac{1}{\sqrt{2\pi}} \exp(-x^2/2) \qquad \text{Eq. 50.2-2}$$

The cumulative standard normal distribution is

$$F_n(X) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{X} \exp(-X^2/2)\, dx \qquad \text{Eq. 50.2-3}$$

50.2.1.2 Tabulations for the normal distribution. Most standard texts have tabulations of both the functions f_n and F_n (for example, reference E-3). In some cases a transformation of the cumulative function of Eq. 50.2-3 is tabulated instead of this function. One excellent tabulation in reference E-7 gives the functions

$$\frac{1}{\sqrt{2\pi}} \exp(-x^2/2) \quad \text{and} \quad \frac{1}{\sqrt{2\pi}} \int_{-X}^{X} \exp(-X^2/2)\, dx$$

as a function of x, as x varies from 0.0 to 7.8. The function $F_n(X)$ may be derived from this second function by the linear transformation:

$$F_n(X) = \frac{1}{2} + \frac{1}{2\sqrt{2\pi}} \int_{-X}^{X} \exp(-X^2/2)\, dx \quad \text{for } X > 0 \qquad \text{Eq. 50.2-4a}$$

$$F_n(X) = \frac{1}{2} - \frac{1}{2\sqrt{2\pi}} \int_{-X}^{X} \exp(-X^2/2)\, dx \quad \text{for } X < 0 \qquad \text{Eq. 50.2-4b}$$

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

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

from which the function $F_n(X)$ may be derived as

$$F_n(X) = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}(X/\sqrt{2}) \qquad \text{Eq. 50.2-6}$$

50.2.1.3 Measured means and standard deviations for a normal distribution. If N values are sampled from a normal distribution with a mean of μ and a standard deviation of σ then the measured mean, $\bar{m}$, follows a normal distribution with a mean of μ and an standard deviation of $\sigma/\sqrt{N}$. The quantity $(N-1)\,S^2/\sigma^2$ is distributed as a chi-squared distribution with N-1 degrees of freedom. This property is sometimes useful for checking the validity of data. (See for example, reference E-1).

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

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

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

$$x_1 \le x_2 \le x_3 \quad \cdots\cdots \quad x_{N-1} \le x_N$$

b. Next to the i'th value, x_i, write the number $i/(N+1)$ to get the following list

x_1	$1/(N+1)$
x_2	$2/(N+1)$
.	.
.	.
.	.
x_{N-1}	$(N-1)/(N+1)$
x_N	$N/(N+1)$

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

If the values of x were drawn from a normal distribution, the plot should be a straight line with intercept (intersection with the 50 percent line) approximately equal to the mean of the distribution and with slope, $\Delta Y/\Delta X$, approximately equal to $1/\sigma$.

As an example, consider the following 10 values drawn from a known normal distribution with mean of 1.0 and standard deviation of 2.0:

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

a. Rank the values according to size

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

b. Make a table for the plot

x	F(Y)	x	F(Y)
-2.230	1/11=.0909	1.478	6/11=.5455
-2.098	2/11=.1818	1.834	7/11=.6364
-1.202	3/11=.2727	1.938	8/11=.7273
-.0342	4/11=.3636	3.152	9/11=.8182
0.596	5/11=.4545	3.564	10/11=.9091

c. plot the points as shown in figure 13.

A fit to the points made by eye gives:

The intercept with the 50 percent ordinate value occurs at x = 0.7 and the reciprocal slope = 2.4

To the accuracy given, these values are the same as would be obtained from Eqs. 50.1-12 and 50.1-13.

50.2.1.5 <u>Analytic tests for normality and for outliers.</u> In addition to the visual check described in paragraph 50.2.1.4, the reader is referred to analytic checks that the distribution is truly normal (reference E-8) and to checks for outliers (reference E-9).

50.2.2 <u>Lognormal Distributions.</u> A lognormal distribution is one where the logarithms of quantities, x, are distributed normally. The frequency distribution function for the lognormal distribution is:

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

where σ_{ln} is the standard deviation in the logarithms of the values of x and μ_{ln} is the mean of the logarithms.

Lognormal distributions occur in situations where a large number of random numbers are multiplied together. Clearly, if the numbers are randomly distributed, then their logarithms are also randomly distributed. Therefore, when the numbers are multiplied together, the logarithm of the result is the sum of many randomly chosen numbers. By the central limit theorem, mentioned in paragraph 50.2.1, the resulting logarithm must be normally distributed.

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

Because the device damage factors of transistors follow a lognormal distribution, (reference E-10), and because this distribution fits many other forms of deterioration due to radiation, (reference E-11) the lognormal distribution is the one which is used almost exclusively in the main text of this document. A more complete discussion of the lognormal distribution may be found in reference E-12.

50.2.2.1 <u>Logarithmic means and standard deviations.</u> Because the lognormal distribution is so important in radiation damage, some formulas and conventions

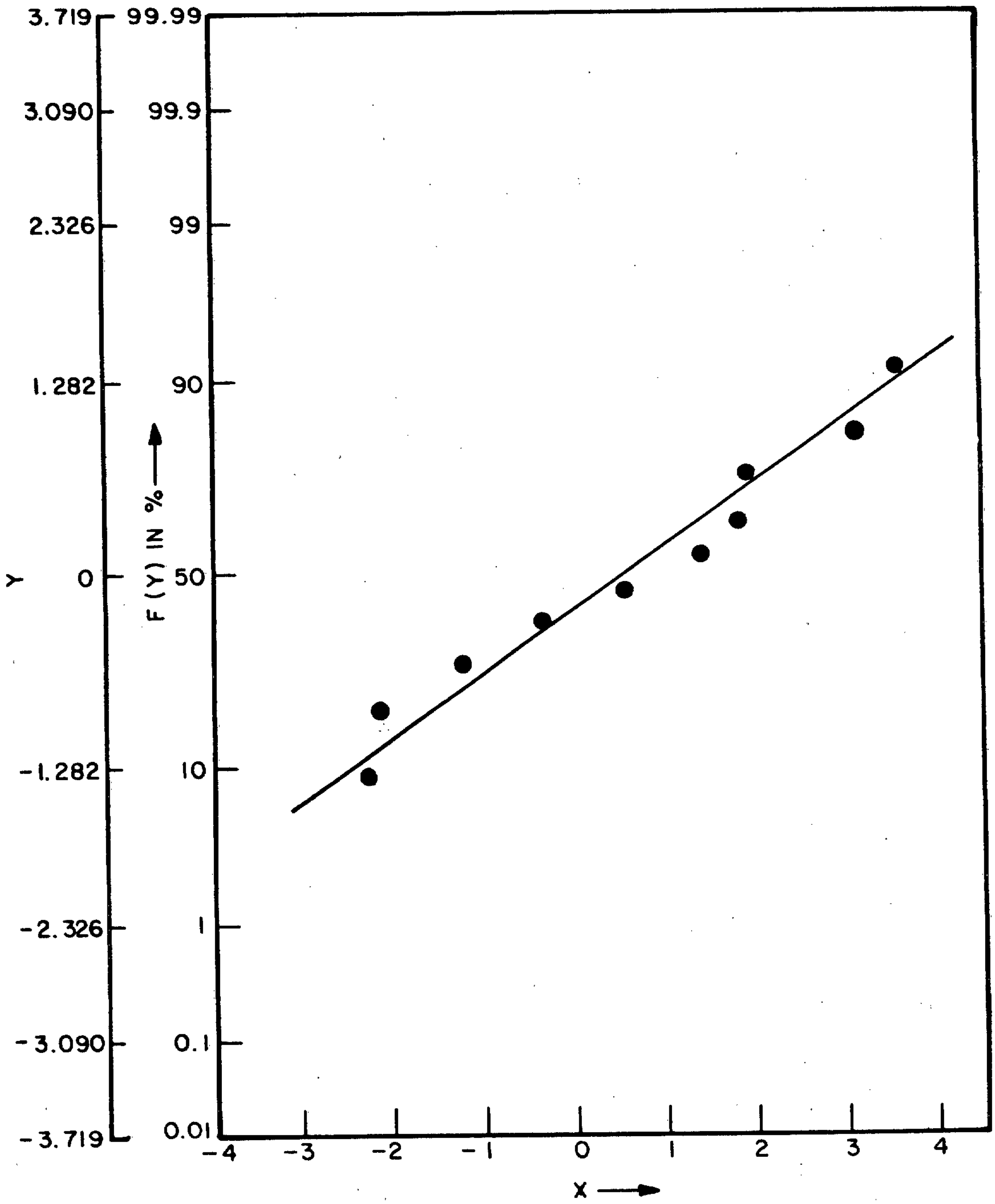


FIGURE 13. Normal probability paper.

useful for this distribution will be given. If the variable x is distributed lognormally, the following quantities are defined:

$$\overline{\ln x} = \text{Measured logarithmic Mean} = \frac{1}{N} \sum_{i=1}^{N} \ln x_i \qquad \text{Eq. 50.2-8}$$

$$S_{1n}^2 = \text{Meas. logarithmic var.} = \frac{1}{N-1} \sum_{i=1}^{N} (\ln x_i - \overline{\ln x})^2 \qquad \text{Eq. 50.2-9a}$$

or

$$S_{1n}^2 = \frac{1}{N-1} \sum_{i=1}^{N} (\ln x_i)^2 - N(\overline{\ln x})^2 \qquad \text{Eq. 50.2-9b}$$

For quantities which are known or assumed to follow the lognormal distribution, the mean value is defined as:

$$X_M = \text{mean value} = \exp(\overline{\ln x}) \qquad \text{Eq. 50.2-10}$$

This expression is somewhat different from the mean given in paragraph 50.1.3.3. The subscript M will always signify that the mean refers to that of Eq. 50.2-10, that is, the geometric mean.

The relations between the arithmetic mean and standard deviation as defined in paragraph 50.1.3.2 and the logarithmic mean and standard deviation of Eq. 50.2-7 are:

$$\mu = \exp(\mu_{1n}) \exp(\sigma_{1n}^2/2) \qquad \text{Eq. 50.2-11}$$

$$\sigma^2 = \exp(2\mu_{1n} + \sigma_{1n}^2) \ (e^{\sigma^2_{1n}} - 1) \qquad \text{Eq. 50.2-12}$$

If the logarithmic standard deviation σ_{1n} is sufficiently small, the lognormal distribution is approximately normal with mean and standard deviation given by:

$$\mu \approx \exp(\mu_{1n}) \qquad \text{Eq. 50.2-13}$$

$$\sigma^2 \approx \mu^2 \sigma_{1n}^2 \qquad \text{Eq. 50.2-14}$$

50.2.2.2 Lognormal probability paper. Lognormal probability paper is exactly the same as normal probability paper except that the abcissa is a logarithmic scale.

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

50.2.3.1 Chi-squared distributions. If N variables are sampled from a standard normal distribution, then the sum of their squares will be distributed as a chi-squared distribution with N-1 degrees of freedom. A good discussion of chi-squared distributions is given in reference E-1. These distributions occur most frequently in assigning a confidence to a measured standard deviation and in testing whether a hypothetical statistical distribution is consistent with measurements. Table A3 in reference E-3 gives a cumulative distribution function for the chi-squared distribution as a function of the degrees of freedom.

50.2.3.2 Exponential distribution. This distribution is frequently used to describe the time between failure of a reparable device or system (or alternatively the time to the first failure for a system which cannot be repaired). A good discussion of this distribution and its applications is given in reference E-2.

50.2.3.3 Weibull distributions. This is a family of distributions which includes all exponential distributions as well as a close approximation to the normal distribution. It is often used for fitting an empirical probability distribution to a set of data. With three adjustable parameters, the Weibull distribution can be used to fit truncated distributions. A good discussion of Weibull distributions is given in reference E-2.

50.2.3.4 Extreme value distributions. Extreme value distributions are the distributions of the largest or the smallest values in a set of randomly selected items or the largest or smallest values over periods of time. Examples are (a) the distribution of the heights of men, each of which is the tallest out of a group of 100 men, or (b) the distribution of the peak temperatures for each year over a period of many years. In statistics, such distributions are often applied to the analysis of outliers. In nature and in economics they are applied to the analysis of unusual (sometimes disastrous) situations such as heat waves, cold snaps, floods, droughts, recessions and so forth. In quality control, such distributions can be important when a system consisting of many parts will fail if even one of the parts fails. In such a case, the probability distribution for failure is the distribution of the weakest out of N parts, where N is the number of parts in the system. Further discussions of extreme value distributions may be found in reference E-3 and E-4.

50.3 Sampling. The aim of sampling is to predict the behavior of a large number of items on the basis of measurements made on a small sample of those items. Most frequently, the results are reported in terms of a confidence, C, that at least a proporation, P, of the lot will not fail under actual use.

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

A note of caution must be interjected here. Most of the sampling techniques report as a confidence the probability that a bad lot will be rejected by a test. However, the probability that a defective lot will be acceptable. While such any assumption be approximately true under most reasonable circumstances, it is easy to imagine cases where it would not work. For example, suppose that all the lots of a certain manufacturer were defective. Even the few lots which passed an acceptance test by chance would still be substandard, and it would be quite incorrect to suppose that the accepted lots met standards with a high degree of probability. Thus, whenever a large fraction of the tested lots is rejected, (a fraction approaching the confidence C) all of the lots should be suspect.

Further discussions of sampling plans are given in references E-2, E-5, and E-6.

50.3.1 Sampling by attribute. In a typical sampling by attribute plan, a sample size, n, is chosen from a lot of size, N, and the number of failures is determined. If the number of failures exceeds a certain acceptance number, c, then the lot is rejected. Reference E-13 gives tables which are used for performing the Lot Tolerance Percent Defective (LTPD) test. For these tables, any lot with more than the listed percent defective stands more than a 90 percent chance of being rejected. It should be noted that in the table of reference E-13, the percent defective refers to the lot before the test was performed. If the tested parts are not returned to the lot (for example, a destructive test), then the test itself influences the percent defective in the remaining lot. For small lot sizes this effect may be significant. Usually, when very high lot qualities are desired, the LTPD method requires an enormous number of parts. However, in some cases there may be an extensive past history of how a device responds under use and, therefore, data for such a large number of tested parts may exist.

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

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

where m is the measured mean as determined by Eq. 50.1-12 and S is the measured standard deviation as determined by Eq. 50.1-13. The one sided tolerance limit, K_{TL} is a functon of the sample size, n, the confidence, C, and the lot quality, P, such that if more than proportion, P, of the parent distribution has values of x less than L_{max}, then the lot will be rejected with probability, C. The limit, L_{max}, is selected such that failure will occur if L_{max} is exceeded. In some cases, the critical value may be a minimum. In these cases, the lot is rejected if the quantity, L, is less than L_{min} where

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

If x is normally distributed with mean μ and standard deviation σ then the quantity $m + K_{TL}\ S$ for a sample size, n, also has a probability distribution (which is slightly different from a normal distribtuion). The one sided tolerance limit, K_{TL} is chosen so that the upper C-fractile of this latter distribution is the same as the lower P-fractile of the original distribution. This condition is illustrated in figure 14.

50.3.2.1 Tabulations and calculations for the one sided tolerance limits. An approximate formula for the calculation of the one sided tolerance limit is given on page 2-15 of reference E-3 and more precise values are given in table A-7 of the same reference, even more precise and more complete tables are given in reference E-14; in that reference, values of K_{TL} may be found for values of P up to 0.9999.

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

50.3.2.1.1 Approximate values of K_{TL} for $P > 0.9999$. If reference E-14 is not easily available, values of K_{TL} for $P > 0.9999$ will be difficult to find. It may be useful here therfore to present a method, not previously published, for obtaining approximate values of K_{TL}. The method uses the values given in Table XII and the formula at the beginning of the table. The method can also be used to obtain values of K_{TL} for values of P which are not included in Table XI. Because values of K_{TL}

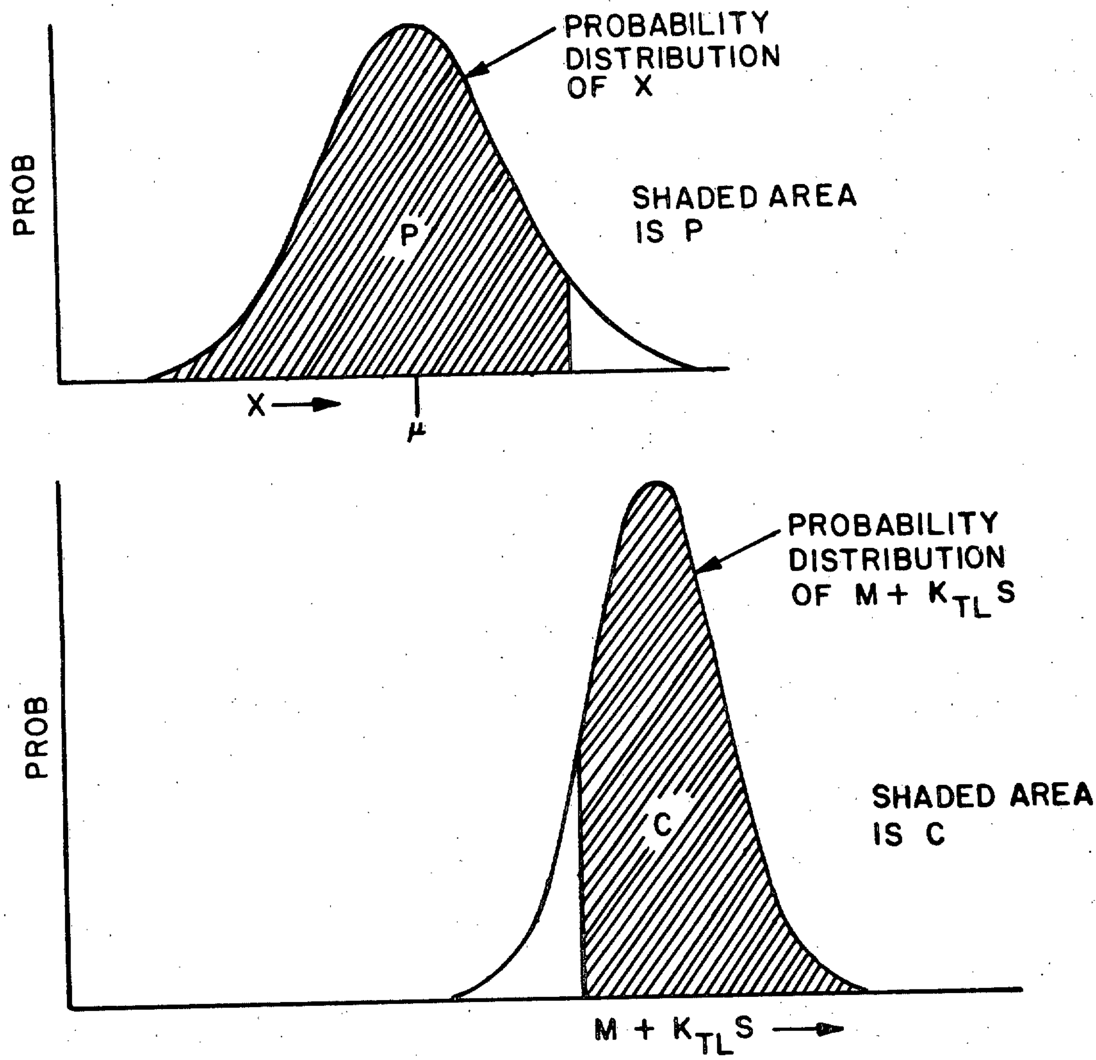


FIGURE 14. One sided tolerance limit.

are usually required for calculating part categorizaton criteria (see paragraph 5.1.6.2 in the main text), Table XII also includes estimated errors for this quantity. The part categorization criteria are based on the formula

$$PCC = \exp(K_{TL}\ S)$$

and the maximum percent error in PCC is

$$PCC = 100/\exp\ (\text{Max Error in } K_{TL})\ /\ (\text{Max } S_{1n})$$

The maximum error in K_{TL} is obtained by comparing the approximate and exact values of K_{TL}. The maximum value of S_{1n} was taken to be 0.5. (see the data of reference E-16 and the calculation of reference E-15.) The error in computing design margins and part categorization criteria for $C \geq 0.99$ is less than 2 percent and is negligible compared to other sources of uncertaTnty (the approximate nature of the probabilities and confidences themselves, possible deviations from the lognormal distribution for complicated devices such as IC's and critical parameters other than a change in the reciprocal gain of a transistor).

50.3.2.1.2 Approximate values of K_{TL} for $P > 0.9$. In some cases, Table XI may be too cumbersome to use and Table XII may be used for values of P down to 0.9 if 10 to 12 percent errors in the design margins and part categorizaion criteria are acceptable.

50.3.2.2 Correcting the sample size in variable sampling plans. It may seem that the sample size is determined by simply counting the number of devices tested. However, to show that this is not necessarily the case, consider the following hypothetical situation. Suppose a manufacturer ships a lot consisting of a large number of devices but the lot is made up of only a few wafer lots. Also, suppose that the devices from a given wafer lot are very uniform as compared to the difference which exist amongst different wafer lots. For illustration purposes, suppose that 5 wafer lots entered into a shipment in approximately equal proportions, and the average parameter x_{avg}. varied from wafer lot to wafer lot according to a normal distribution. A measurement on a large number of devices would give the probability distribution in figure 15. Even if thousands of individual devices were used in a measurement, since the major cause of variation amongst the devices was the wafer-lot variations, and only 5 wafer lots were sampled, the true sample size is only 5. In such case, calculations for one-sided tolerance limits and so forth should use the value 5 for the sample size.

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

Clearly, for any measurement there is an effective sample size which will always be equal to or less than the actual number of devices measured. The determination of this size is a somewhat complex procedure involving the chi-squared tests are described in reference E-15. Such tests should be standard procedure - especially for characterization measurements - to check the fit of the data to the assumed probability distribution.

50.4 Calculation of survival probabilities. The ultimate goal of a probability analysis is to calculate the survival probability of a system. A common practice for obtaining a most conservative estimate that a system composed of N parts from a lot will survive is

$$P_{Survival} = C\ P^N$$

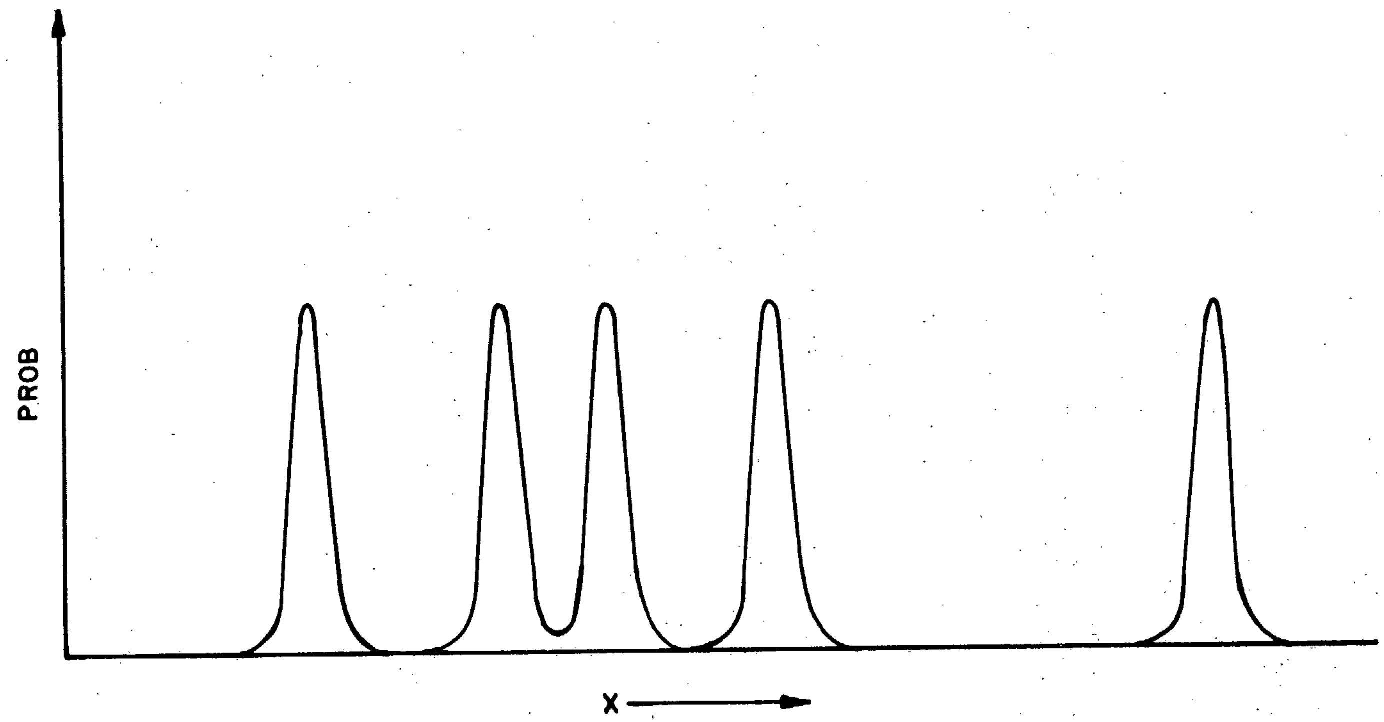


FIGURE 15. Hypothetical shipment with 5 wafer lots.

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

50.4.1 Monte Carlo simulations. In extremely complicated situations where a fairly precise estimate must be made for the survivability of a circuit or a system it may be necessary to perform a Monte Carlo simulation of the system behavior on a computer. A good fundamental introduction to such simulations is given in reference E-16. Monte Carlo analyses are frequently used in problems such as shielding calculations and neutron transport calculations (see for example reference E-17). The basic idea is to simulate parameters which vary according to a given probability law by picking random numbers which vary according to the same law. In practice, the methods for arriving at a reasonably precise answer without consuming too much computer time are quite sophisticated and expert advice would be essential. The reader should be aware of what such techniques have to offer. Their advantages are:

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

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

The disadvantages are:

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

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

APPENDIX E

Table XI: One-Sided Tolerance Limits, K_{TL}.

C = 0.9

P

N	0.9	0.95	0.99	0.999	0.9999
3	4.259	5.311	7.340	9.651	11.566
4	3.188	3.957	5.438	7.129	8.533
5	2.742	3.400	4.666	6.111	7.311
6	2.493	3.091	4.243	5.555	6.645
7	2.332	2.894	3.972	5.202	6.222
8	2.218	2.755	3.783	4.955	5.927
9	2.133	2.649	3.641	4.771	5.708
10	2.065	2.568	3.532	4.628	5.538
11	2.011	2.503	3.443	4.514	5.402
12	1.966	2.448	3.371	4.420	5.290
13	1.928	2.403	3.309	4.341	5.196
14	1.895	2.363	3.257	4.273	5.116
15	1.867	2.329	3.212	4.215	5.046
16	1.842	2.299	3.172	4.164	4.986
17	1.819	2.272	3.137	4.119	4.932
18	1.800	2.249	3.105	4.078	4.884
19	1.781	2.228	3.077	4.042	4.841
20	1.765	2.208	3.052	4.089	4.802
21	1.750	2.190	3.028	3.979	4.766
22	1.736	2.174	3.006	3.952	4.734
23	1.724	2.159	2.987	3.926	4.704
24	1.712	2.145	2.969	3.903	4.677
25	1.701	2.132	2.952	3.882	4.651
30	1.657	2.080	2.884	3.794	4.546
35	1.623	2.041	2.833	3.729	4.470
40	1.598	2.010	2.793	3.678	4.411
45	1.576	1.986	2.761	3.638	4.363
50	1.559	1.965	2.735	3.605	4.324
60	1.532	1.933	2.694	3.552	4.262
70	1.511	1.909	2.662	3.513	4.215
80	1.494	1.890	2.637	3.482	4.178
90	1.481	1.874	2.617	3.456	4.148
100	1.470	1.861	2.601	3.435	4.124

APPENDIX E

Table XI: One-Sided Tolerance Limits, K_{TL} - Continued.

C = 0.95

P

N	0.9	0.95	0.99	0.999	0.9999
3	6.157	7.655	10.553	13.857	16.597
4	4.162	5.145	7.042	9.214	11.019
5	3.406	4.202	5.741	7.502	8.966
6	3.006	3.707	5.062	6.611	7.900
7	2.755	3.399	4.642	6.063	7.244
8	2.582	3.188	4.353	5.687	6.796
9	2.454	3.031	4.143	5.413	6.469
10	2.354	2.911	3.981	5.203	6.218
11	2.275	2.815	3.852	5.036	6.020
12	2.210	2.736	3.747	4.900	5.858
13	2.155	2.670	3.659	4.787	5.723
14	2.109	2.614	3.584	4.690	5.608
15	2.068	2.566	3.520	4.607	5.509
16	2.032	2.523	3.463	4.535	5.423
17	2.001	2.486	3.414	4.571	5.448
18	1.974	2.453	3.370	4.415	5.281
19	1.949	2.423	3.331	4.363	5.221
20	1.925	2.396	3.295	4.318	5.167
21	1.905	2.372	3.263	4.277	5.117
22	1.886	2.349	3.233	4.239	5.073
23	1.869	2.329	3.206	4.204	5.031
24	1.853	2.309	3.181	4.172	4.993
25	1.838	2.292	3.158	4.142	4.958
30	1.777	2.220	3.063	4.022	4.816
35	1.732	2.167	2.995	3.934	4.712
40	1.697	2.123	2.941	3.865	4.631
45	1.669	2.093	2.898	3.811	4.566
50	1.645	2.065	2.862	3.766	4.513
60	1.609	2.022	2.807	3.695	4.430
70	1.581	1.990	2.765	3.642	4.368
80	1.559	1.965	2.733	3.601	4.319
90	1.542	1.944	2.706	3.567	4.279
100	1.527	1.927	2.684	3.539	4.246

Table XI: One-Sided Tolerance Limits, K_{TL} - Continued.

C = 0.99

P

N	0.9	0.95	0.99	0.999	0.9999
3	13.998	17.372	23.896	31.348	37.532
4	7.379	9.084	12.387	16.175	19.327
5	5.362	6.579	8.939	11.649	13.906
6	4.411	5.406	7.335	9.550	11.395
7	3.859	4.728	6.412	8.346	9.957
8	3.497	4.286	5.812	7.564	9.024
9	3.240	3.973	5.389	7.014	8.368
10	3.048	3.739	5.074	6.605	7.881
11	2.898	3.556	4.829	6.288	7.503
12	2.777	3.410	4.633	6.035	7.201
13	2.677	3.290	4.472	5.827	6.954
14	2.593	3.189	4.337	5.652	6.747
15	2.521	3.103	4.222	5.504	6.571
16	2.459	3.028	4.123	5.377	6.419
17	2.405	2.963	4.037	5.265	6.287
18	2.357	2.905	3.960	5.167	6.170
19	2.314	2.854	3.892	5.079	6.066
20	2.276	2.808	3.832	5.001	5.974
21	2.241	2.767	3.777	4.931	5.890
22	2.209	2.729	3.727	4.867	5.814
23	2.180	2.694	3.681	4.808	5.745
24	2.153	2.662	3.640	4.755	5.681
25	2.129	2.633	3.601	4.706	5.623
30	2.030	2.516	3.447	4.508	5.389
35	1.957	2.430	3.334	4.364	5.219
40	1.902	2.364	3.249	4.255	5.090
45	1.857	2.312	3.180	4.168	4.987
50	1.821	2.269	3.125	4.097	4.903
60	1.764	2.203	3.038	3.987	4.774
70	1.772	2.153	2.974	3.906	4.677
80	1.688	2.114	2.924	3.842	4.602
90	1.661	2.083	2.883	3.791	4.542
100	1.639	2.056	2.850	3.748	4.492

Table XI: One-Sided Tolerance Limits, K_{TL} - Continued.

C = 0.999

P

N	0.9	0.95	0.99	0.999	0.9999
3	44.429	55.111	75.775	99.385	118.979
4	16.120	19.814	26.978	35.203	42.047
5	9.781	11.970	16.223	21.114	25.190
6	7.246	8.849	11.964	15.549	18.539
7	5.920	7.223	9.754	12.668	15.098
8	5.112	6.234	8.415	10.924	13.018
9	4.569	5.573	7.521	9.763	11.633
10	4.180	5.098	6.881	8.932	10.643
11	3.886	4.741	6.401	8.309	9.902
12	3.655	4.462	6.026	7.824	9.324
13	3.470	4.238	5.726	7.436	8.861
14	3.317	4.053	5.478	7.116	8.481
15	3.189	3.899	5.272	6.849	8.164
16	3.080	3.767	5.096	6.622	7.894
17	2.985	3.653	4.944	6.427	7.662
18	2.903	3.554	4.813	6.257	7.460
19	2.830	3.466	4.696	6.107	7.282
20	2.765	3.388	4.592	5.974	7.124
21	2.706	3.319	4.500	5.855	6.982
22	2.654	3.256	4.417	5.748	6.856
23	2.606	3.199	4.341	5.651	6.741
24	2.563	3.147	4.272	5.562	6.636
25	2.523	3.099	4.210	5.482	6.540
30	2.364	2.910	3.960	5.162	6.161
35	2.251	2.775	3.783	4.935	5.893
40	2.165	2.673	3.649	4.764	5.691
45	2.097	2.593	3.545	4.630	5.532
50	2.042	2.528	3.460	4.522	5.405
60	1.957	2.428	3.330	4.357	5.209
70	1.895	2.355	3.234	4.235	5.065
80	1.846	2.298	3.160	4.141	4.955
90	1.807	2.252	3.101	4.066	4.866
100	1.775	2.214	3.052	4.004	4.793

Factors K_{TL} such that with confidence, C. at least a proportion, P, of a normal distribution will be less than

$$m + K_{TL}S$$

where m and S are the measured mean and standard deviations respectively.

The factors K_{TL} are presented as function of C, P, and the sample size, N, used in measuring m and S.

Table XII: Values for Calculating Approximate One-Sided Tolerance Limits.

C = 0.9

N	A	B
3	3.0808	0.4503
4	2.2658	0.4190
5	1.9393	0.3875
6	1.7621	0.3604
7	1.6499	0.3376
8	1.5719	0.3183
9	1.5141	0.3018
10	1.4694	0.2875
11	1.4337	0.2750
12	1.4043	0.2639
13	1.3797	0.2540
14	1.3587	0.2452
15	1.3406	0.2371
16	1.3248	0.2298
17	1.3108	0.2232
18	1.2983	0.2170
19	1.2871	0.2113
20	1.2770	0.2061
21	1.2678	0.2012
22	1.2594	0.1966
23	1.2517	0.1924
24	1.2446	0.1883
25	1.2380	0.1846
30	1.2112	0.1686
35	1.1914	0.1561
40	1.1761	0.1460
45	1.1638	0.1376
50	1.1536	0.1305
60	1.1378	0.1191
70	1.1258	0.1102
80	1.1164	0.1030
90	1.1088	0.0971
100	1.1025	0.0920

Estimated Maximum Errors in Computing Part Categorization Criteria for N > 5

	Percent Error
$P \geq 0.9999$	0.6
$P \geq 0.9$	2

Table XII: Values for Calculating Approximate One-Sided Tolerance Limits - Continued.

C = 0.95

N	A	B
3	4.4154	0.5157
4	2.9200	0.4932
5	2.3724	0.4628
6	2.0893	0.4345
7	1.9154	0.4096
8	1.7971	0.3881
9	1.7110	0.3694
10	1.6452	0.3530
11	1.5931	0.3384
12	1.5506	0.3255
13	1.5153	0.3139
14	1.4854	0.3034
15	1.4597	0.2939
16	1.4373	0.2852
17	1.4176	0.2773
18	1.4001	0.2699
19	1.3845	0.2631
20	1.3704	0.2568
21	1.3576	0.2509
22	1.3460	0.2454
23	1.3353	0.2402
24	1.3255	0.2353
25	1.3165	0.2308
30	1.2797	0.2113
35	1.2528	0.1960
40	1.2320	0.1836
45	1.2154	0.1733
50	1.2017	0.1645
60	1.1805	0.1503
70	1.1645	0.1393
80	1.1520	0.1303
90	1.1419	0.1229
100	1.1336	0.1166

Estimated Maximum Errors in Computing Part Categorization Criteria for N > 5

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

APPENDIX E

Table XII: Values for Calculating Approximate One-Sided Tolerance Limits - continued.

C = 0.99

P

N	A	B
3	9.9749	0.5998
4	5.1112	0.6033
5	3.6692	0.5820
6	3.0034	0.5559
7	2.6230	0.5304
8	2.3769	0.5069
9	2.2043	0.4856
10	2.0762	0.4665
11	1.9771	0.4493
12	1.8980	0.4337
13	1.8333	0.4196
14	1.7792	0.4067
15	1.7332	0.3948
16	1.6936	0.3840
17	1.6592	0.3740
18	1.6288	0.3646
19	1.6019	0.3560
20	1.5777	0.3479
21	1.5560	0.3403
22	1.5363	0.3332
23	1.5184	0.3266
24	1.5019	0.3203
25	1.4868	0.3143
30	1.4262	0.2889
35	1.3825	0.2688
40	1.3491	0.2523
45	1.3227	0.2386
50	1.3012	0.2268
60	1.2680	0.2078
70	1.2433	0.1929
80	1.2241	0.1808
90	1.2086	0.1707
100	1.1958	0.1621

Estimated Maximum Errors in Computing Part Categorization Criteria

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

Values of K_{TL} such that with confidence C at least proportion P of a normal distribution is less than

$$m + K_{TL}S$$

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

$$K_{TL} \simeq A\overline{F}_n(P) + B/\overline{F}_n(P)$$

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

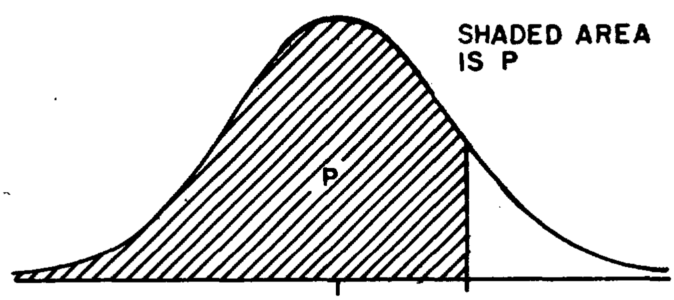
$\mu + \overline{F}_N(P)\,\sigma$

The values of A and B are listed in columns 2 and 3 respectively as functions of C and N. A few values for $\overline{F}_n(P)$ are given in Table XIII.

Table XIII. The Anti-function of the Standard Normal Distribution.

$\overline{F}_n(P)$ is such that for a normal distribution with mean, μ, and standard deviation, σ, proportion P of the distribution is less than

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



P	.9	.95	.99	.999	.9999	.99999	.999999
$\overline{F}_n(P)$	1.282	1.645	2.326	3.090	3.719	4.265	4.753

P	.1	.05	.01	.001	.0001	10^{-5}	10^{-6}
$\overline{F}_n(P)$	-1.282	-1.645	-2.326	-3.090	-3.719	-4.265	-4.753

APPENDIX E

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* Available from the National Technical Information Center, Springfield, VA 22161, under this order number.

APPENDIX F

RADIATION TESTING

10. GENERAL

10.1 Scope. This appendix addresses the common test requirement for all devices.

20. REFERENCED DOCUMENTS

Not applicable

30. DEFINITIONS

Not applicable

40. GENERAL REQUIREMENTS To establish a neutron data base using the test procedures in method 1017 of MIL-STD-883.

50. RADIATION TESTING

50.1 Radiation Sources. The most widely used sources of neutrons for hardness assurance testing of electronics are nuclear reactors of either the TRIGA or Fast Burst Reactor (FBR) type. The DNA TREE Simulation Facilities Handbook provides information on 18 pulse reactor facilities. Under free-field conditions FBRs provide a larger ratio of neutron-to-gamma radiation dose and provide a higher average energy of neutrons which in turn produces less residual radioactivity of the samples. The use of cadmium shields to reduce the activation of piece parts at TRIGA reactors is not recommended because this may greatly enhance the gamma-to-neutron ratio. Boron shielding such as Flex-shield is recommended for this purpose. Properly used, either type of facility can provide satisfactory hardness assurance testing if the environment can be properly specified in terms of dose to the critical region of the device under test.

Isotopic sources and accelerators can also be used as neutron sources, but their utility is generally limited because of their low output. Caution must be used if monoenergetic neutron sources such as those from the (D,T) reaction are used for damage equivalence testing. In this case the ratio of damage functions does not include flux-weighted averaging for the source; therefore, the damage at the source of energy must be accurately known.

50.1.1 Neutron fluence. The environment in which the critical region of a piece-part is exposed (i.e. that provided by the source and modified by shields, reflectors and packaging) must be characterized in terms of the radiation parameter specified and any other parameters that may affect the outcome of the test. Specifications for neutron hardness are most often expressed in terms of that portion of the neutron energy which is deposited into atomic collisions in silicon. An artifice widely used to express this "displacement dose" is 1-MeV equivalent (Si) fluence which assumes a displacement damage cross section at 1-MeV neutron energy. Thus, the product of the specified 1-MeV equivalent (Si) fluence and the displacement cross section is the silicon displacement dose that the piece part must survive. The accepted value for the silicon displacement cross section at 1-MeV is 95 MeV mb (or 3.27×10^{-11} rad (Si)/n/cm^2). This value will appear in versions of ASTM standard E722 dated after 1983 (reference F-1). The neutron spectrum in free-field irradiations at fast burst reactors is 1-MeV equivalent (Si) (i.e. the spectrum weighted displacement cross section at an FBR is approximately 3.27×10^{-11}). At TRIGA reactors, the 1-MeV equivalent (Si) fluence is about 50 percent of the total fluence. The free-field 1-MeV equivalence for FBRs and TRIGAs is summarized in Table 1. These values may vary from facility to facility because the displacement dose is determined by integrating the neutron spectrum for that facility against the silicon damage function (ASTM E 722).

The principle of equivalent damage has broad applicability, but the "damage dose" must be specified and a parameter proportional to damage must be known as a function of neutron energy. Thus, 1-MeV equivalent (Si) fluence is not strictly applicable to gallium arsenide parts. An appropriate damage function is required for a specification in terms of dose. The same damage function can be integrated against the facility neutron spectrum to determine the irradiation required to produce equivalent damage. Alternatively, a neutron spectrum and level may be specified along with a material of interest. One may then either employ a damage function or attempt to tailor the neutron spectrum to fit the specified spectrum.

Table XIV. Determining the test fluence.

Quantity Specified	Provided by facility	TRIGA multiply facility fluence by	FBR multiply facility fluence by
Φ 1 MeV (Si)	Φ Total	0.5	1
Φ 1 MeV (Si)	Φ (>10 keV)	0.8	1
Φ 1 MeV (Si)	Φ (>3 MeV	11	7

Irradiation can be performed in either pulse or steady state mode. The numbers in the accompanying tables may vary from facility-to-facility and at different locatons within the facility. It is recommended that, if irradiations are performed in heavily shielded configurations, neutron spectrum measurements be made to determine the damage equivalence in that environment.

50.1.2 Gamma dose. The gamma dose that accompanies neutrons can produce significant degradation of piece parts. The neutron-to-gamma ratio can sometimes be adjusted to simultaneously meet specified neutron displacement and ionizing dose levels. However, it is usually desirable to obtain a high neutron-to-gamma ratio to separate the effects of the two types of damage. If separate gamma and neutron tests are to be performed, it is desirable to determine the gamma sensitivity of the parts prior to neutron testing to aid in the design of shields and selection of the neutron source. The neutron-to-gamma ratio can be varied over a wide range by selection of the source (FBR or TRIGA) and by selection of appropriate shielding. The highest neutron-to-gamma ratios can be obtained at FBRs with high atomic number shields such as lead (Table 2). The highest gamma-to-neutron ratio are obtained at TRIGAs with cadmium or CdO loaded polyethylene shielding. Ionizing dose at reactors is typically measured with thermolumiescence dosimeters (TLDs). For irradiation of silicon parts CaF:Mn TLDs shielded by 60 to 90 mils of aluminum are recommended. Lithium-7 fluoride TLDs may be used, but appropriate corrections must be applied. The calibraiton and use of TLDs in electronics testing is described in ASTM Standard E688-78 (reference F-2).

The presence in reactors of low energy photon components has not been established; however, it is likely that such components are present especially in TRIGA reactors. If component packaging contains high atomic number material such as kovar or gold, it is advisable to irradiate parts and gamma dosimeters in a shield consisting of 1/16-inch of lead lined with 1/16-inch of aluminum to reduce dose enhancement effects.

Table XV. Neutron-to-Gamma Ratios.

	TRIGA Φ 1-MeV/rad(Si)	FBR Φ 1-MeV/rad(Si)
Free-Field	3 to 9 x 10^8	4 x 10^9
Attentuated (2" lead)	7 x 10^9	1.4 x 10^{10}

APPENDIX F

References:

F-1 Standard Practice for CHARACTERIZING NEUTRON ENERGY FLUENCE SPECTRA IN TERMS OF AN EQUIVALENT MONOENERGETIC NEUTRON FLUENCE FOR RADIATION-HARDNESS TESTING OF ELECTRONICS, ASTM E 722-80.

F-2 Standard Practice of the Application of THERMOLUMINESCENCE-DOSIMETRY (TLD) SYSTEMS FOR DETERMINING ABSORBED DOSE IN RADIATION-HARDNESS TESTING OF ELECTRONIC DEVICES, ASTM E 668-78.

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NEUTRON HARDNESS ASSURANCE GUIDELINES
FOR
SEMICONDUCTOR DEVICES AND MICROCIRCUITS

MIL-HDBK-280, dated 19 February 1985, is hereby canceled and superseded by MIL-HDBK-814, "Ionizing Dose and Neutron Hardness Assurance Guidelines for Microcircuits and Semiconductor Devices".

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