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13. ABSTRACT

It is the purpose of this document to provide persons conducting TREE (Transient Radiation Effects on Electronics) experiments with recommended procedures which experience has shown are efficient for determining transient-radiation effects on electronic parts. Areas which are covered in detail are experimental design, experimental documentation, dosimetry and environmental correlation, and preferred measurement procedures for diodes, transistors, capacitors, and microcircuits.

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TREE

PREFERRED PROCEDURES

(Selected Electronic Parts)

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IN COLLABORATION WITH MANY SCIENTISTS AND ENGINEERS WHOSE ASSISTANCE
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Advisory Group

A limited group of individuals outstanding in the area of transient-radiation effects was selected to serve in an advisory capacity for the development and subsequent revision of this document. The purpose of this group was to give guidance for this document's development and to review and comment in detail on the drafts of the report. Battelle acknowledges the indispensable help of these men as advisory group members.

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TREE PREFERRED PROCEDURES

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1.0 GENERAL INFORMATION

1.1 BACKGROUND

The technology of Transient Radiation Effects on Electronics (TREE) covers a wide range of scientific and engineering disciplines. It is a specialized field and, not surprisingly, has developed a jargon of its own, borrowing concepts and terms from solid-state physics, radiation and nuclear physics, nuclear-weapon technology, electronic engineering, and systems engineering. In the past, the TREE community comprised a relatively small group of researchers and experimenters who could easily communicate and exchange information. However, now that many systems must meet radiation specifications, the community is expanding and reorienting itself toward more systems applications. Hence, a primary goal of much of the experimental work pertaining to TREE is gathering information needed to fill the gap between state-of-the-art information already available and the requirements of a specific system. Obviously, it is neither desirable nor efficient to unnecessarily duplicate experimental work. On the other hand, it is usually not economically possible to acquire experimentally all the data in a particular region of interest that might be desirable from the viewpoint of a regular scientific research study. The Defense Nuclear Agency (DNA) has recognized the need to exert a unifying influence on the TREE community to achieve a more efficient utilization of experimental and financial resources.

In pursuit of this task, DNA has undertaken a program to bring to the attention of the electronic engineer, designer, and researcher those procedures in testing and experimentation which experience has shown to be most likely to yield useful results that can be correlated with other work in the same area. To this end, this document is meant to provide persons conducting TREE experiments with recommended procedures that experience has shown are efficient for determining transient-radiation effects on electronic parts.

1.2 PHILOSOPHY

The recommendations in this document are a consensus of current good practice. Many people in the TREE field, in electronics-system design, and in semiconductor-device manufacturing were contacted. Their opinions and methods were evaluated and judiciously merged to form the basis for this work. The results presented are considered neither controversial nor "far out". Many of the procedures recommended here are already followed by various competent groups involved with TREE. If one procedure is obviously best, it

is recommended; if several procedures are equally acceptable, all are presented for the user's choice. The object has been to formulate and recommend procedures by which radiation-test data on electronic components and radiation environments may be obtained and reported.

In this connection it is important to realize what these preferred procedures are and what they are not. They are a formal recognition of good practices and methods based on sound physical principles which can lead to useful TREE data. They provide a means of communicating useful information among workers in a large multidisciplined technology, so that people in different subspecialties (e.g., dosimetry, circuit design, component testing, system specification, or component fabrication) will be able to use one term in place of various specialty terms to better understand one another.

These preferred procedures are not necessarily simplifications. They are not the formulation of recipes by which a person unfamiliar with TREE can become an expert chef by "cooking" up new data. They are not a panacea for hardened-systems designers, electronics engineers who do not want to understand physics, or physicists who do not want to bother with applications. Sound scientific judgment and a basic understanding of the problems still are necessary attributes for the TREE experimenter.

This document is prepared as an integral part of a series of documents sponsored by DNA to assist and guide the TREE community. Other documents in this series are the TREE Handbook, TREE Simulation Facilities, EMP Handbook, Nuclear Environment Descriptions and a Management Guide to TREE.

It is assumed that the users of this document will have access to the TREE Handbook and the other documents in this series. The intelligent use of these preferred procedures relies on the user being familiar with the information contained in the TREE Handbook. Therefore, a thorough review of the pertinent subjects in the TREE Handbook is strongly recommended as a first step in planning any TREE experiment.

1.3 USE OF THIS DOCUMENT

Who Should Use the Document?

Four principal types of users are expected to use this document: (1) circuit and system designers who use component data; (2) system specifiers - i.e., those in government agencies or others who perform tradeoffs to formulate environment criteria, system performance specifications, and system-failure criteria; (3) component manufacturers who can provide basic physical and electrical data and have the fabrication techniques and process control needed both for development of harder components and for

design assurance; and (4) the user to which this document is primarily directed, experimenters in TREE who perform and define tests, including environment correlation, to obtain and report radiation-response data on electronic components for use by designers. Although this document has been prepared for use by anyone who performs an experiment in the TREE area, Sections 2.0, Experimental Design, and 3.0, Experimental Documentation, should be of value to all experimenters and to those managers responsible for TREE experimental programs. It will aid them in developing efficient plans.

User Responsibility

It should be realized that the material contained in this document is considered the best available at the present time; however, as the state of the art advances, so will test and experimental procedures. As a result, this document will evolve as improvements are realized and a broader need for component-part testing is recognized. It is important that the experimenter realize this and (1) use only the most recent edition of the Preferred Procedures and (2) take an active part in supplying new information to effect improvements. Only in this way can this document grow in sophistication and utility. The last section, entitled Miscellaneous, contains a form for suggesting deletions, additions, or corrections to this publication.

The user should also realize that he bears the burden when simplifying or deviating from the suggested procedures. That is, he must justify any deviations from the suggested procedures and report his work in sufficient detail to explain the deviations completely.

1.4 LIMITATIONS

Several areas of testing and test results are not included in this document. The first area is radiation chemistry. For the present, the document will cover only those effects of radiation which pertain to electrical behavior and not the chemical changes that may occur. Second, long-term ionization effects are not included although they are recognized as a problem area to be covered in future documents. It is felt at this time that sufficient information is not available to provide an adequate discussion of this topic. For the same reason, the third area, laser simulation, is not covered. Fourth, large scale or high-volume testing was not considered in the description of the test procedures. The principles presented in this document are applicable to high-volume testing. However, instrumentation for this type of testing probably will have to be specially designed, unless the radiation facility to be used already has such equipment and it is applicable to the test program.

It should be understood that these component part measurement procedures were established to apply principally to design data acquisition and reporting and not to radiation-effects research or system tests. For some theoretical studies the experimenter may want to investigate new phenomena or methods which would require use of different procedures or would study other parameters than those discussed here. In any case, the detailed experimental procedures actually used must be reported completely enough for another person to understand and repeat the experiment.

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2.0 EXPERIMENTAL DESIGN

2.1 INTRODUCTION

For every development program, all available knowledge should be utilized and all supplemental information necessary to meet program requirements should be gathered; this avoids waste of experimental and financial resources and reduces the time required for system development. Implied is careful organization of the test efforts in the program, a goal which can be achieved by applying proven test and documentation procedures.

A well documented experimental design provides much of the input information needed for scheduling, financing, and managing the total program as well as the experimental work. It not only specifies the experimental work to be accomplished and the results expected, but also provides a basis for integrating experimental work into a development program in an efficient and effective manner.

A good experimental design document will contain much of the information needed for the final report that describes the experimental results. Thus, the effort spent in preparing and documenting the experimental design prior to experimentation would be expended in any case prior to publication of the experimental results. Insofar as possible, then, it is a good practice to anticipate final report format in the test planning documentation.

In all branches of science and technology, principles and techniques have evolved that are pertinent to this task of designing engineering experiments. The basic principles and techniques applicable to designing experiments for determination of transient-radiation effects on electronic parts are compiled in the following paragraphs.

2.2 EXPERIMENTAL DESIGN PRINCIPLES

Since many books and articles have been written about experimental design, the subject will be discussed here only briefly, as it applies to TREE tests. The cardinal principle to follow in designing an experiment is to prepare a complete and detailed plan, in writing, before beginning the experiment. The problem generally encountered is not that experimenters do not understand this principle but rather that some important planning may be neglected while meeting test schedules and balancing program budgets.

The development of an experimental design provides more or less detailed answers to the following questions:

(1) Experimental Purpose: What is the problem?

(2) Experimental Objectives: What information is needed to solve the problem?

(3) Pretest Analysis Procedures: What analysis or prediction methods can be used to produce this information? How valid is the theory?

(4) Requirements for Experimental Data: What experimental data are needed to solve the problem or some aspect of it?

(5) Experimental Procedures: What must be done experimentally to obtain these data?

(6) Posttest Analysis: How are the data best analyzed in the required terms for this problem?

The documentation of an experimental design should contain answers to these questions and may be divided into six parts corresponding to them. In the final report, a section will contain the observed data and its analysis, along with general and specific conclusions as pertinent.

Experimental Purpose

Defining the problem to be solved often leads to optimal approaches for solution. Therefore, the statement of the problem – the purpose of the experiment – is an important part of the test design. In very brief form, the purpose of most TREE tests to which these preferred procedures are applicable will be either to support some TREE-hardened system design or the TREE assessment of a system. System-design support might involve determination of radiation responses of a group of devices for design application data, or it might take the form of screening tests for acceptance. The definition of the problem for a pretest document, then, would include (1) the system design or assessment radiation criteria (or a reference to them if they are classified and if the pretest plan must be unclassified); (2) a statement as to how the system design or assessment has been divided into subtasks; (3) a statement as to how a specific subtask involves the tests about to be described and performed; (4) some statement concerning required accuracy of the test data in order to support the subtasks or tasks.

Test Objectives

The specific objectives of the test are stated clearly to ensure that the test data will support the system problem and that the test design will achieve

the necessary results. For example, the system design requirement may be for photocurrent data on a group of high-frequency power transistors along with a complete electrical modelling characterization. (Neutron degradation data on these devices might be the subject of another test plan.) Certain data-accuracy requirements, numbers of test devices, and gamma-ray rate ranges are consistent with the system design philosophy. Certain data formats are required by the designers and, perhaps, by the contractor developing the system. These test objectives and constraints should be listed as completely as possible.

Pretest Analysis Procedures

In the design, it is important to build on existing technology. Therefore, what is already known about the test objectives and techniques, as well as expected results, should be referenced. This procedure demonstrates the relevance of the particular test being designed.

Most TREE experiments to which this document applies measure electronic device parameters before, during, and/or after radiation exposure. Since these electrical parameters are related to an application requirement or a response model, some predictive analysis may be made as a basis upon which test results may be judged. In the test design, pretest analysis methods should be described in detail, and test results should be predicted approximately. This will ease the measurement process and also demonstrate applicability of the expected results to the system task at hand. This pretest analysis may lead to significant changes in the test design if unexpected results are found. This is normal and proper, since experimental design is inherently a dynamic process, subject to revision as new data or understanding become available. These changes, of course, also ought to be documented.

Analysis procedures for TREE phenomena are outlined in this volume and detailed in the TREE Handbook, DNA H-1420-1. Discussion of the validity of theory underlying the pretest analysis may be in order for some parameters. The significant assumptions should be set down, especially those related to the system problem of which the test is to be a part. (For example, environmental synergistic effects may be important.) These questions should be addressed in pretest analysis and in its documentation.

Experimental Data Requirements

This section is critical to test design, since it defines specifically the types and quantities of samples, accuracies, operating conditions, environments, and other parameters relating to the test. The test objectives and

existing information and the planned analysis methods should be considered in establishing (1) the format, (2) the list of required parameters and their dependencies, (3) the accuracies, (4) the numbers of test items, (5) environmental ranges, and (6) any contractual requirements such as traceability of calibration standards. Very likely, some compromises will need to be made; for example the radiation environments may be mixed (or separated) in particular ways at the available source facility, or the number of data points will be limited for nontechnical reasons.

Statistical test design should be used when suitable to provide controls, proper numbers of test groups, and sample sizes to meet the system confidence requirements. The assignment of test-sample sizes is not a trivial problem, nor can statistical methods be blindly applied to the TREE experimental design. One reason for this is that the distributions of semiconductor-device parameters are likely not to be normal but, rather, truncated by manufacturers' process controls and screening tests. Another reason is that most of the tests envisioned will be designed to elicit device parameters as functions of operating conditions and environments rather than in terms of a "failure level" or "go-no-go" criteria; screening tests are an obvious exception. These points will be taken up in detail in Section 2.4.

The other elements of the test data requirements (1-3 and 5 above) are discussed in the succeeding chapters of this document.

Experimental Procedures

The test planning approach being outlined here includes the selection of test procedures. Consideration of the data requirements and constraints, based on system requirements and pretest analysis, may indicate some particular test procedures. There may be such "real-life" considerations as availability of personnel, equipment, radiation facilities, or even of test items. Ultimately, the test engineer should apply the physical principles of TREE technology within whatever other constraints he may have. This document contains specific recommended "preferred" procedures for many types of TREE data tests on transistors, diodes, integrated circuits, and capacitors as aids to the test engineer.

The test procedures section of an experimental design should include (1) specific means for eliminating or controlling sources of systematic errors; (2) descriptions of the experimental subtasks and how these tasks integrate into the whole test to produce the desired result; (3) required measurement-equipment lists, along with their calibration and accuracy or precision requirements; (4) specific procedures, such as those given in this document, including circuit diagrams, operating ranges, equipment dial

settings (if applicable), and other details of the test; (5) radiation-source-characterization details and means of obtaining desired exposures; and (6) specific plans for data analysis.

Posttest Data Analysis

Typically, the raw TREE test data will be oscilloscope photographs, punched cards from a semiconductor test set readout, or tabulated sets meter readings. Posttest data analysis involves three processes (1) interpretation of raw data in terms of appropriate electrical quantities and units, including reading errors and equipment accuracies; (2) interpretation of these electrical quantities in terms of test objectives, required parameters, device models, predicted responses, etc., including the experimental uncertainties inherent because of the procedures and sample sizes; and (3) interpretation of unexpected data points in terms either of experimental errors or some uncontrolled or unknown phenomenon.

In the pretest documentation, the appropriate posttest analysis methods should be specified in detail for the test.

2.3 ANALYSIS OF EXPERIMENTAL DATA

The analysis procedures given in an experimental design description specify the techniques to be used to translate the raw data into useful information. For any type of experiment the objectives will require that the analysis procedures produce an orderly arrangement (tabular and/or graphic) of the experimental data as measured and, where appropriate, in reduced form. Detailed procedures should be specified for data reduction.* A description of the procedures for evaluating measurement precision and systematic experimental error and the methods for combining these to estimate the experimental error and accuracies should be included. Error bands should be included and identified (e.g., ranges, standard deviation, etc.) on all graphs. Accuracies should be stated in all tables of numeric data.

The general rule for selecting analysis techniques for inclusion in the analysis procedures section of the experimental design document is to select the simplest technique that will fulfill the stated objectives and purpose of the experiment. Actually, the only restrictions placed on the selection of analytical techniques is that they must

* Data reduction is used here to denote the derivation of more meaningful parameters by combining the values of measured parameters. For example, resistivity may be derived by combining measured voltage, current, and dimensional values; neutron fluence expressed as neutrons per cm^2 (E > 1 MeV) may be derived combining activation dosimetry values, reactor spectra information, and shielding data. Data reduction may also mean the computation of descriptive statistics, the normalization of data by taking ratios, etc. Making value judgments or predictions of any kind are not included in data reduction.

(1) Satisfy the experimental objectives

(2) Determine the confidence associated with any conclusions reached

(3) Estimate the experimental accuracy for all numerical results.

The selection and specification of analysis procedures for an experimental design is primarily an engineering responsibility. The engineer should consult appropriate references in the speciality with which the experiment is concerned as well as more general references concerned with experimental design, data analysis, and statistics as appropriate.* If at all possible, early consultation with specialists in data analysis, statistics, and the design of experiments is recommended.

For the preferred measurement procedures given in this document, the data reduction and analysis techniques usually are defined inherently by the experiment. Thus, if transistor gain as a function of collector current and neutron fluence is needed (the experimental purpose), the test procedures outlines would result in sets of raw data that can be reduced by straightforward methods to obtain the desired gain data. In this process of data reduction, it is important to track the sources of uncertainty and error: measurement errors in currents, counting errors in dosimetry, etc. Then the results and probable errors are quoted. This data reduction process is clear for the problem of determining response of one or a few devices.

The quest might have been, however, not simply to determine the response of one device, but rather to determine what is the expected radiation-response distribution of a population of devices of which a sample was selected for test? This question involves the entire test design to ensure proper sampling of the population, proper measures to control errors, etc., as well as the analysis of the response data of the irradiated group(s) of devices. In this case, some statistical interpretations will have to be made. For example, for a given experimental fluence, the gains as functions of collector current may be split out of the data and analyzed to find, for several specific values of I_C, the mean observed gain and the observed standard deviation of the gain for the sample. From this, assuming proper randomizing of the sample and assuming fixed process controls, a statistical inference may be made with specified confidence concerning the parts-population mean gain and variance for this fluence at these collector currents. This process could be repeated for other fluence values. Alternatively, the gain versus fluence, or damage constant data, could be analyzed for specified I_C values to arrive at the same result. More complex statistical inferences concerning multiparameter distributions could also be determined, but they may not be worth the effort. A specialist in statistical inference should assist in their use.

* See Bibliography.

An assumption normally made that may not be valid is that the parts response distributions are gaussian. It may be one function of the test to determine the actual population distribution with some degree of certainty. This may lead to use of "non parametic" statistical analysis of data - again, an area for specialists.

One desired engineering result for TREE test data is often curves of gain or photocurrent or other quantity plotted as functions of an electrical or radiation parameter. This involves fitting a curve to the measured (and reduced) data. It is convenient to express the data in terms that theoretically could be plotted linearly, e.g., reciprocal gain versus fluence or peak photocurrent versus dose rate. Then, least squares and regression analysis can be used to determine how well the data fit, what slopes and intercepts are given with confidence, etc. More simply, such curves can be "eye-balled" if the statistical detail is not needed.

When the curves are not linear and/or the functional relations are not analytic, the purpose of the experiment will usually determine what effort is worthwhile in performing more complex statistical analyses.

For "go-no-go" tests, such as acceptance screening of parts by testing for a certain parameter (or a few such parameters), the statistical design of the test is generally easier to establish. Here, the distribution of data is binomial and the techniques are well established. (The part either passes or fails a test, depending on the radiation response, but the parts-response distribution itself is not the entity in view; the data are the "passes" or "fails", a "go" or a "no-go" for a given test item, or a fraction passing, p, and failing, $q = 1-p$ in the population. Based on the number of failures in a sample drawn from the parts lot being accepted and on the system requirements, determination of the probability that the population failure rate will be within specified limits, using binomial distribution statistics, is straightforward. (See books by Lloyd and Lipow, Bazousky and Roberts in the Bibliography.)

For system assessment work, it is more likely that only a few parts can be found for tests, and the analysis technique must glean the most information from the test. This calls for careful test design and, perhaps, the use of "small-sample" statistics and tolerance factors - an area for a specialist.

As stated previously, the experimental design should include a detailed specification of the methods to be used to evaluate measurement errors and experimental accuracy. For further guidance in the development of this section of the experimental design, the engineer is referred to the discussions of the nature of error and sources of experimental error by J. W. Richards in Interpretation of Technical Data.

2.4 SAMPLE SIZE DETERMINATION

In TREE test design, the selection of the sample for test depends strongly on the purpose of the test. As indicated earlier, screening tests use the binomial distribution,

$$P(x \leq c) = \sum_{x=0}^{c} \binom{N}{x} p^x q^{N-x} ,$$

where P (x < c) is the probability that the number of passed items, x, is no greater than the acceptance test level number, c, for the test sample size, N, and p is the actual probability of a single item's passing the test, with q = 1-p. Curves and nomographs of this distribution may be used to decide on sample size, N, and acceptance test level, c. The test engineer should consult statistical texts or specialists for details of application to his problem. (See, also, MIL-STD- 19500 or 38510 for sampling plans and acceptance criteria.)

For parametric design data on components and devices, the accuracy with which the data must be known for the specific system design applications will determine the sample sizes for tests. Also, the spreads in the data themselves and the uniformity of parts responses will influence the sample size, as will the actual shapes of the distributions. This implies that there needs to be some processing control of parts manufacturing to provide reasonable uniformity of response and that the sample set selected for test must adequately represent the parts population to be used in the system design.

To be much more specific than the last paragraph one must plunge into a detailed discussion of statistical methods considering confidence (or tolerance) limits for the system design data, allocation of parts for tests depending on their design margins in the system, etc. These factors are system dependent and complex, and we shall not pursue general mathematical approaches here. However, as a rule of thumb and as a matter of common practice, many test engineers have found between ten and thirty samples adequate to define the parameters of principal interest to system designers for neutron and gamma ray effects on semiconductor parts. Mean damage constants or photocurrent slopes (in the linear range) do not usually become appreciably better known by increasing test sample size above thirty for those parts types which have been fabricated with the same technologies and controls.* Normally, system designers invoke enough margins so that the mean values of radiation-affected parameters and their distributions (variance or higher moments) need not be known to high accuracy. It therefore is recommended that, for parametric design data on components and devices, a sample size between ten and thirty be

* For 90% confidence, 90% of a normal population will differ from the sample mean by no more than a tolerance factor, K, times the sample variance, with K decreasing only by about 25% (from 2.0 to 1.7) as N goes from 10 to 30.

used depending on the system design margins and requirements for confidence in the design hardness. In addition, for system hardness assurance samples for irradiation tests are often picked from selected production lots of a particular device type. Typically a sample size between ten and thirty is considered adequate for radiation sampling tests of a particular production lot. In some cases, such as the statistical evaluation of systems performance, an analysis might show the need for more parts tests, or the data spreads in the test itself might indicate such a need. Then, clearly, this "rule of thumb" should not be taken as a firm guide.

2.5 EXPERIMENTAL HARDWARE CONSIDERATIONS/TECHNIQUES

Introduction

A sequence of general experimental hardware and technique considerations will now be addressed.

In the normal process, the experimenter must first consider how to characterize the semiconductor device to be tested. This characterization may be repeated one or more times after the test. Secondly, he must select the proper irradiation facility to meet the objectives of the test. This subject is discussed in Section 4.0. Then he must measure the selected response of the device under irradiation. In making this measure there are several important points to be considered. These include choosing the proper operating mode for the device while it is being exposed to radiation, and making choices between pre and post vs. *in situ* measurements. There are also important considerations of suppression of the unwanted side effects of the radiation or the radiation source, such as electrical- and radiation-induced noise and thermal effects, which cannot be ignored. Finally, the experimenter must choose the techniques that are needed to properly characterize the radiation to which the device was exposed. This subject is discussed in detail in Section 5.0.

Characterizing the Test Device

The measurements to be performed on the test device before exposure to radiation are generally of two types. Mandatory are those measurements in which the important radiation-induced changes are expected to occur. For example, the displacement effect of radiation on the h_{fe} of a transistor is almost always a part of the reactor test program. In addition to these measurements, it is desirable to perform other measurements by which the particular test device can be characterized. It is known that even within a particular device type number there are large variations of individual device

characteristics. These are usually within the parameter specification, but occasionally one finds devices whose characteristics fall outside of the specifications under which the devices were supposedly purchased. Since it is desirable to be able to associate the radiation response with preirradiation measurements, it is good practice to include in the parts characterizations, those parameters which are likely to be correlated with the radiation response. Example of such a measurement would be f_t of a transistor, or any other parameter dependent upon the transistor base width.

When planning for a test at a radiation facility, several basic considerations and test-design decisions, which are not related to the measurement of a particular parameter, must be made. Some of these are outlined here as an aid to designing experiments and using this document.

The construction characteristics of commercially available semiconductor devices may be a source of uncertainty in the results obtained when these devices are irradiated. The construction characteristics of semiconductor devices that have the same electrical specifications (same device number) may be substantially different if obtained from separate manufacturers or even from different production lots from one manufacturer. These differences in production procedure may have a significant effect on the radiation responses of the devices. The effect of processing details on radiation response are particularly important when radiation-induced surface effects are studied. For these reasons, the characterization of samples from various production lots is advisable to obtain results that will be truly representative of the radiation response of a particular device type.

Depending upon data requirements, it may be necessary to exercise some control over the samples obtained from the device manufacturer. Samples with identical construction but with tighter initial-parameter spreads may be required to satisfy system specifications for the intended application and to obtain greater internal consistency in the test results. If controlled samples are used, it is important to identify them as accurately as possible when reporting test results.

There are several ways in which permanent-damage tests can be conducted. Tests in which parameter measurements are made only before and after the samples are removed from their irradiation position are called "pre/post tests". They serve to establish the damage incurred at a single irradiation level. Since the samples are normally not energized during irradiation, these tests are the most convenient, least complex, and least expensive tests to perform. Since measurements can be made in the laboratory (and samples shipped to and from the radiation facility), it is possible to test a statistically significant number of samples and measure them at several operating points of interest. Such pre/post tests are useful as proof tests to establish adequate device performance at a given radiation level, as long as time dependence and bias dependence are not important. Usually the experimenter has to wait for the radioactivity induced in the test devices to decay somewhat before returning them to a test laboratory.

Data may be obtained at several irradiation levels by simply repeating a pre/post test as many times as desired, or by exposing different groups of samples to various radiation levels. The first procedure is more time-consuming and, since it involves repeated physical orientation in the radiation environment, may be subject to errors. Due to differences in the radiation response of different experimental samples, certain parameter data obtained by exposing different samples to increasing irradiation levels may exhibit a lack of internal consistency (i.e., there may not be a smooth pattern of parameter change with increasing irradiation exposure). Also it is commonly observed that when extended periods (typically greater than 8 hr) without irradiation are present during a test, the sample parameter values sometimes change (due to defect annealing) so that data taken before and after the cessation do not correlate well. Therefore, measurements should be made at the beginning and end of such periods, if possible.

Tests in which the experimental samples are instrumented at the irradiation facility so that parameter measurements can be made without removing the samples from their irradiation position are called "in-place tests". They serve to characterize the radiation response at various irradiation levels and/or at specific time intervals during and after irradiation exposure. The requirement for test equipment and extensive cabling at the test facility makes in-place testing more complicated and more expensive than pre/post tests. The in-place experiment may require extensive instrumentation if a significant number of samples are tested.

Normally, more than one parameter will be measured in a test. The sequence of parameter and operating-point measurements should be carefully considered since this affects the duration of the measurement period and the device temperature. Also, because injection level and power dissipation influence defect recovery, the sequence of measurements after any irradiation should be from low-current to high-current operating points so that no data will be lost due to significant defect recovery which might occur during high-current testing.

While for permanent damage measurements, the choice of pre/post vs. in situ experiments is optional, it is obvious that with transient effect data the measurements have to be performed during and immediately after the radiation pulse. The response of a device under test depends upon the radiation pulse width. For pulses much shorter than the device electrical response time, the magnitude of the response usually depends upon total dose and its duration is a function of the device recovery time. For pulses long compared to the device response time, the instantaneous response tends to follow the dose rate. The test circuit can affect the observed response time by intentional or even inadvertent capacitive loading of the terminals of semiconductor devices which have high impedance circuits in series with this capacitance. In establishing a transient effects test program, it is necessary to understand the role played by the intrinsic device response time, such as inherent conductivity relaxation, and the response times influenced by external parameters.

For this reason, it is necessary always to report, accurately, the electrical loading of the device under test including the resistance and capacitance connected to its external terminals.

Transistors and Diodes

The basic methods of making parametric measurements on transistors and diodes are the steady-state method and the pulsed method. The most common and simplest technique is to apply steady-state sources (either dc or ac) to the test circuit and observe the desired response while varying one or more of the sources in discrete steps. Aside from its simplicity and low cost, this method has the advantage of simulating steady-state behavior quite well. Unfortunately, as power dissipation increases, the junction temperatures increase, altering many of the parameters of the device. If the ultimate application of a particular device is in the pulsed mode, the data taken at the higher power levels using the steady-state technique will yield inapplicable results. The pulsed method of parameter measurement minimizes changes in junction temperature and may also be used to simulate actual operating conditions for a particular circuit design. Applied pulses must have sufficient duration to insure that responses have reached the electrical steady-state (not thermal). The pulse repetition rate (duty cycle) should be kept low to minimize device heating.

For matched-pair devices it is often desirable to determine the changes in differential device parameters. The most satisfactory technique is to make a differential measurement. Although such techniques are not detailed here, the experimentalist can readily modify suggested measurement circuitry to provide for differential measurements.

An example of a simple and relatively fast method of obtaining many (but not all) parameters at many operating points is by using a curve tracer to sweep out a family of device characteristics and display them on an oscilloscope. Both steady-state and pulsed measurements can be made using this method. The displayed characteristics should be photographed to provide a permanent record that can be used for pretest and posttest comparisons. This method typically yields data with an uncertainty of at least 5 percent so it is not recommended for critical design-data purposes. It should be used only when device parameter changes of more than 15 percent of preirradiation values are expected.

The choice of a particular measurement method must involve consideration of the ultimate circuit application of the device (if known), accuracy requirements, cost limitations, the number of measurements to be made, and methods of data reduction. If the application of a particular device is not unique, it is wise to employ several of the above-mentioned techniques to acquire several kinds of data. Regardless of the particular method(s) chosen, conditions should be identical for preirradiation and post-irradiation measurements, as far as possible. In case a large number of measurements are

planned, consideration should be given to automating the measurements and the data-reduction procedure. Although such methods are not described here, the suggested measurement circuitry can be modified to allow for automated measurement schemes and machine-oriented data reduction.

Sometimes the leads of a sample are shortened after pretest measurements to facilitate subsequent test purposes. The shorter leads may affect the relation between pretest and posttest measurements in two ways. First, at high currents, the voltage drops in the leads may be significantly different in the two cases; this can be measured and a correction made. Second, changing the lead length may change the case-to-ambient thermal resistance; this can readily change the case temperature by 20 C or more and cannot be easily compensated. Therefore, every effort should be made to keep the lead lengths constant, and the device should be well heat-sinked for measurements.

Unwanted oscillations during an electrical measurement can render the measurement invalid. The following are suggested ways to eliminate oscillations of test circuits:

(1) Use shielded cable or coaxial cable to minimize coupling between the transistor elements.

(2) Locate an appreciable part of the collector-circuit resistance as close to the transistor as possible.

(3) Place ferrite beads on the leads of the transistor.

(4) Bypass with a capacitor the collector to the emitter and/or the base to the emitter.

(5) Provide degenerative feedback through a pulse transformer.

Microcircuits

The choice of a particular measurement method for a microcircuit must involve consideration of the ultimate circuit application of the device. If the application of a particular device is not unique, it is wise to employ several techniques to acquire the kinds of data which are needed. Regardless of the particular method(s) chosen, conditions should be identical for preirradiation and postirradiation measurements, as far as possible. In case a large number of measurements are planned, consideration should be given to automating the measurements and the data-reduction procedure. Although such methods are not described here the suggested measurement circuitry can be modified to allow for automated measurement schemes and machine-oriented data reduction.

A very critical step in the process of testing is determining what constitutes significant response and failure of a device. The system requirements

obviously must be used to define component failure. Usually these failure criteria are much lower than would be normally expected because of circuit tolerances which are used to establish a "worst-case" failure criterion. The failure criteria for the components of a given system must be carefully determined by considering all electrical parameters of a device in its system application. Because logic circuits are usually not the limiting factor in the displacement effects radiation hardness of a system, the worst case failure criteria can often be assumed for each logic circuit application even though this specification is conservative in most cases. This eliminates the necessity of developing failure criteria for each circuit application, and because logic circuits are relatively hard, the cost involved with this overspecification will probably be reasonable.

On the other hand, linear circuits are almost always softer than logic circuits, and it is often both advantageous and necessary to examine each application in detail to determine failure criteria. The necessity of each specification limit must be carefully considered, because if the required specification is too strict, a heavy cost may result when circuits are selected which are hard to the required level.

Measuring the Response to Radiation

One of the first choices that must be made is that of the operating of the mode of the device during irradiation. Whether the measurements in a permanent damage experiment are to be made on a pre/post or *in-situ* basis, one must choose the bias point for the devices during radiation exposure (one option is unbiased and unconnected). In performing transient effects experiments it is obviously necessary to bias the devices in an interesting operating region. Since transient measurements must usually be taken rapidly, only one bias point can be checked per exposure, although a number of exposures at different bias points can be given without changing the inherent characteristics of the device. For the observation of maximum effect in some permanent damage experiments, especially those associated with surface effects on semiconductor devices, it is necessary to have the devices under bias during irradiation with the bias maintained throughout the post-irradiation measurement. In these cases, it is usually more convenient to perform all of the measurements *in situ*.

The irradiation levels at which data are taken normally depend upon the end purpose of the data. It is normally desirable for data analysis and presentation purposes to obtain data at approximately equal logarithmic intervals of radiation exposure, such as $10^{(x)}$, $3 \times 10^{(x)}$, and $10^{(x+1)}$, or $2 \times 10^{(x)}$, $5 \times 10^{(x)}$, and $10^{(x+1)}$.

Regardless of the particular test technique chosen, adequate dosimetry (including energy spectrum) for each group of samples is of prime importance. It should be emphasized that adequate dosimetry during reactor irradiations

includes gamma dose measurements. At pulsed reactors the n/γ ratio can be measured for a particular experimental configuration. At steady-state reactors, provision should be made for a low-power gamma dosimetry run. The value obtained can be scaled to the experimental power level. This run can sometimes be performed several days in advance of the actual test. If an attenuating shield is to be introduced during the test, spectral measurements should be made with and without the shield. For experiments performed at gamma radiation sources the gamma dose rate can be monitored and the total dose determined from the total irradiation time or an integrating dosimeter can be used to measure the total dose.

The choice of dose rate(s) at which to irradiate semiconductor devices for ionization effects is a prime consideration. Testing over a wide range of dose rates is almost always required in order to fulfill the data requirements of the designer. The choice of the number of dose rates at which to make the measurements will be a function of the particular device (type and manufacturer) and its intended application. In the absence of detailed application information, measurements should be made at each decade of dose rate, $\dot{\gamma}$, over a dose rate range from 3×10^5 to 3×10^{10} rads (Si or Ge)/s. This extends from a low range where the response is usually linear to a high value where the device is saturated in most circuit applications. The justification for measurements over such a wide range of dose rates is that some devices do not conform to a linear dependence of I_{pp} on $\dot{\gamma}$, and such a series of measurements will reveal the range of rates over which these nonlinearities exist.

When repetitive pulsing is employed or when high dose rates and/or long pulse widths are involved, it is easy to build up large doses in the sample. Above 10^4 rads (Si or Ge) some devices (particularly low-speed or high-voltage units) may incur significant permanent damage. Such damage is evidenced as an increase in junction leakage. When this threshold is exceeded, the sample dose should be reported, and a clear identification made of the data that was obtained above the threshold. Justification should be given for using such data.

The photocurrent response of a device is, to some extent, dependent upon the energy spectrum of the ionizing-radiation source, especially for spectral components with energies less than 0.5 MeV. Therefore, an effort should be made to control and/or measure the spectrum, as well as the dose rate. This is particularly important if it is suspected that the incident spectrum at the sample location has changed (e.g., due to the interposition of shields).

Most transistors and diodes are in the class of "thin samples", and their responses are independent of orientation in a homogeneous, high-energy radiation beam. High-power devices, however, may have thick-walled cases or mounting studs which in some orientations act to shield the active device volume (semiconductor chip) from the radiation. If such orientations cannot be avoided, the orientation used should be recorded and an effort made to determine the actual dose received by the active volume.

The radiation response evidenced by a sample, particularly at low currents, is quite temperature dependent. Temperature rise may occur due to power dissipation in the device, gamma-ray heating of the sample, or simply a high ambient temperature. Temperature rise in a material due to gamma-ray heating may be calculated from the specific heat capacity C_p (cal/gm· C) and the dose D in rads as

$$\Delta T = 2.39 \times 10^{-6} \frac{D}{C_p} .$$

Since many device parameters vary with temperature, inplace measurements should include provisions for monitoring the sample temperature and, if necessary, controlling it. In general measurements should be made at temperatures varying no more than 3 C from the basic reference temperature, which usually is room temperature, unless a specific application requires otherwise. However, if it is anticipated that device heating will be a problem during in-place measurements, it is suggested that a higher reference temperature be chosen within the allowed device operating temperature range (usually 35 C). This choice simplifies the temperature-control system. Only a sensing element and a heater are required in this case; natural cooling is then adequate, which avoids complex cooling systems. In this case, for proper correlation, all laboratory characterization should be made at the temperature used for the measurements made during the irradiation. It is recommended that the temperature variations during irradiation be limited to ±15 C about the reference temperature, insofar as practicable. The device temperature should not be allowed to exceed 70 C for silicon devices since the rate of annealing increases rapidly beyond this temperature.

Noise Suppression

Noise Coupling Modes

Conducting transient radiation effects experiments presents some severe problems to the experimenter. Generally, these experiments require transmitting small signals over long cables in the vicinity of a powerful pulsed radiation source. Careless handling of the signals can result in the loss of data, or in questionable data. Therefore, it is mandatory that the experimenter maintain as high a signal-to-noise ratio as possible.

There are a number of ways in which noise can be injected into an experiment. To the electronic measuring system used in an experiment, the pulsed radiation source is a large noise generator. Associated with the radiation pulse is an electromagnetic field which can propagate through the shielding and into the measuring circuit. The generator can also introduce noise on the 60-Hz power line which, in turn, couples the noise into the experiment through test equipment connected to the 60-Hz line. These noise

sources are in addition to the 60-Hz interference which must be avoided even in steady-state experiments.

When multiple ground points are used, ground loops or common-mode returns permit noise from the pulsed radiation source, or from any other noise source, to get into the measuring system. Capacitive coupling can serve as ground connections at high frequencies.

Crosstalk between cables and mismatching between equipment and cable impedances can contribute significantly to the degradation of signal quality.

In the case of a pulsed source of ionizing radiation, such as a LINAC or flash X-ray, another source of noise is the charge transferred between the source and the test box and the test circuitry. An illustration of charge transfer is given in Figure 2.1 and shows that the charge is not only transferred from the main beam source but also between the sample and its surrounding environment. The charge transfer is maximized in the electron-beam mode, but is also significant in the bremsstrahlung mode due to the production of energetic electrons by Compton and photoelectric interactions. Typical charges transferred between surfaces are $\sim 1 - 5 \times 10^{-12}$ C/rad(Si) per cm^2 of surface area. Obviously measurement of currents in devices having a response $\lesssim 10^{12}$ C/rad(Si) requires special care.

Another example of charge transfer occurs in coax cables. The best solid dielectric cables exhibit a net charge of $\sim 10^{-15}$ C/(rad·cm) of irradiated cable. The worst (foam or semisolid insulator type) are up to a factor of 1000 larger. These responses can also depend on irradiation and voltage history. Neutrons produce responses varying from 10^{-25} to 10^{-21} (C·cm)/n. The conductance may also be important at higher voltages, and ranges from 2×10^{-17} to 10^{-15} mho·s/rad·cm, even in solid cables.

Air ionization caused by the radiation sources can also introduce spurious and misleading signals. Typical air-ionization leakages due to short pulses yield a conductivity of $\sim 10^{-14}\ \dot{\gamma}$ (mhos/cm), where $\dot{\gamma}$ is the ionization dose rate in rads/s. This can be minimized by operating the experiment in a vacuum, provided the pressure is maintained below one micron, or by encapsulating the test sample in an insulator. However, secondary electrons produced in the potting material can also introduce erroneous signals. When an experiment is being conducted in a vacuum chamber or cassette, the effects of the secondary electrons produced by the bremsstrahlung radiation entering and leaving the test box can be minimized, but not eliminated, by using thin low-Z window material. If this proves insufficient, a magnet can be used to sweep the electrons away from the test sample.

Another source of potential noise interference is the pulsed magnetic field produced by the electron current associated with a photon beam. The field is generally solenoidal about the direction of the photon beam, and can be estimated from the known equilibrium between photon and electron currents.

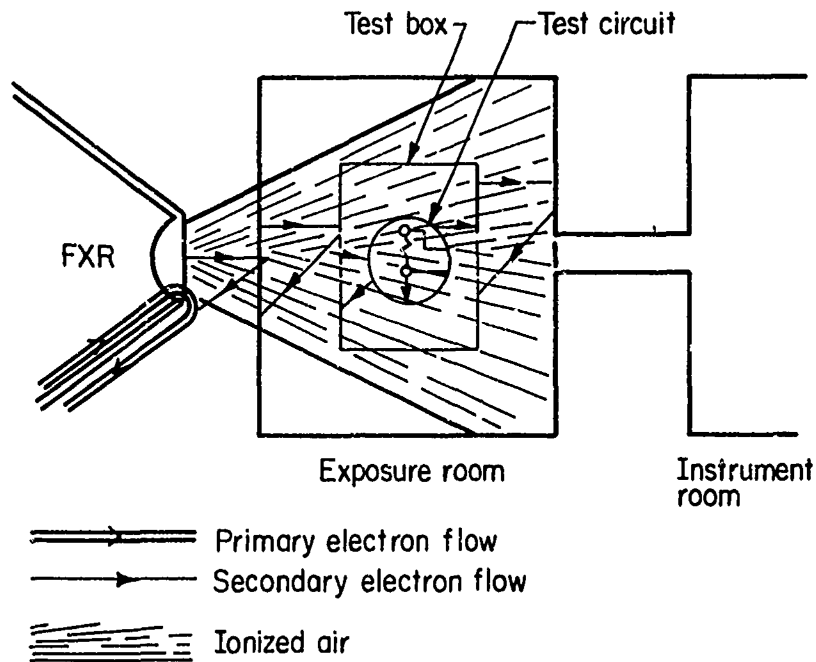


FIGURE 2.1. CHARGE TRANSFER PATHS

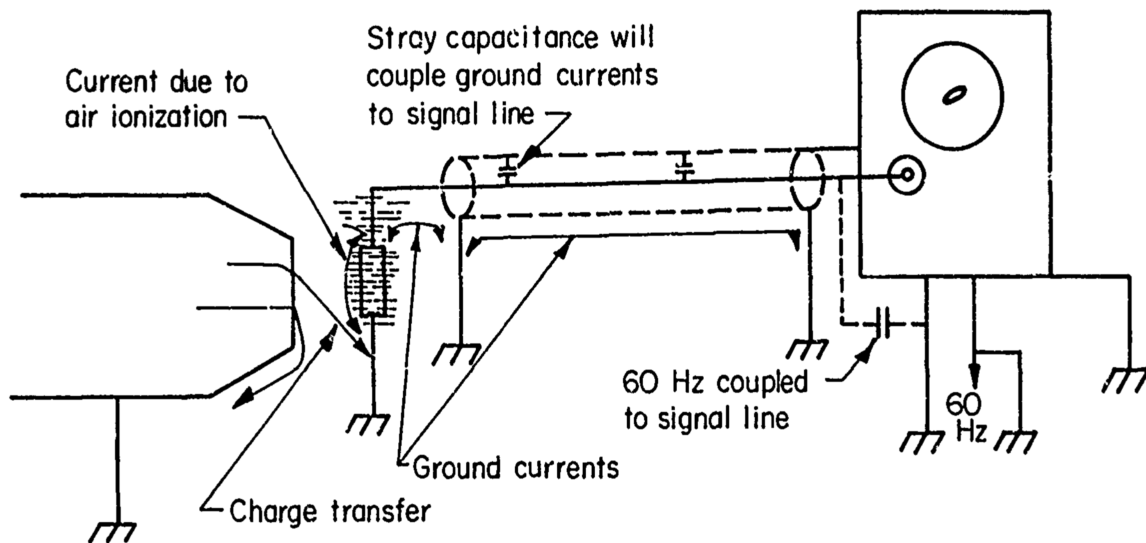


FIGURE 2.2. TYPICAL NOISE SOURCES

The effect of this field can be eliminated by proper shielding and avoidance of loops in cabling configurations.

Figure 2.2 depicts some of the ways described above in which noise can be introduced into a system.

Noise Minimizing

Techniques used to minimize noise in electronic systems are fairly well understood, although often disregarded. As few ground points as possible should be used, preferably only one. High-frequency signals should be handled in a coaxial configuration with the shield being continuous and, where possible, differential measurement techniques should be used. If a high-frequency differential measurement is to be made, coaxial cables for each side should be used. The two cables should be the same length and tied together so that any noise picked up in the cables will be of the same phase and magnitude and, hence, cancel each other in the differential mode. At lower frequencies, twinaxial cables or shielded-twisted pairs provide better common-mode signal rejection. In extreme electromagnetic fields, experiments should be enclosed in a cassette, with the interconnecting cables between the exposure and instrumentation rooms enclosed in a continuous shield such as "zip" tubing, again grounded at only one point. Triaxial cable can also be used. Grounding of the shielding and the low side of the measuring circuit should be located as close to each other as possible to prevent ground loops. Where it is necessary to provide 60-Hz power to some portion of the experiment, the low side of the 60-Hz power should not be connected to or used as the signal return line. An improved experimental setup is shown in Figure 2.3.

In general, when selecting a grounding point, it is not advisable to use the pulsed radiation source for this purpose since it is probably the largest source of noise in the vicinity of the experiment. However, in the case where charge transferred from the radiation source to the experiment is a noise problem, a ground or connection between the experiment and the source may become necessary to avoid persistent noise oscillations. LINACS or flash X-ray machines used in the electron beam mode must have a ground return. To be effective, this connection must have a very low inductance; otherwise, there will be a significant voltage buildup during the pulse which can then be coupled to the measuring circuit.

Another example of a setup in which separate shield rooms enclose the target and recording equipment is shown in Figure 2.4. The charge transfer to the cassette is transferred back to the wall of the target shield room via the outer shield of a triaxial cable, a zipper tube, or at best a solid shield pipe. The test specimen is floated inside the cassette (but inevitably couples to it capacitively) and is connected via coaxial cable to the recording station, at which the circuit common is connected to a master earth. This system can also be used with balanced cable pairs and line drivers.

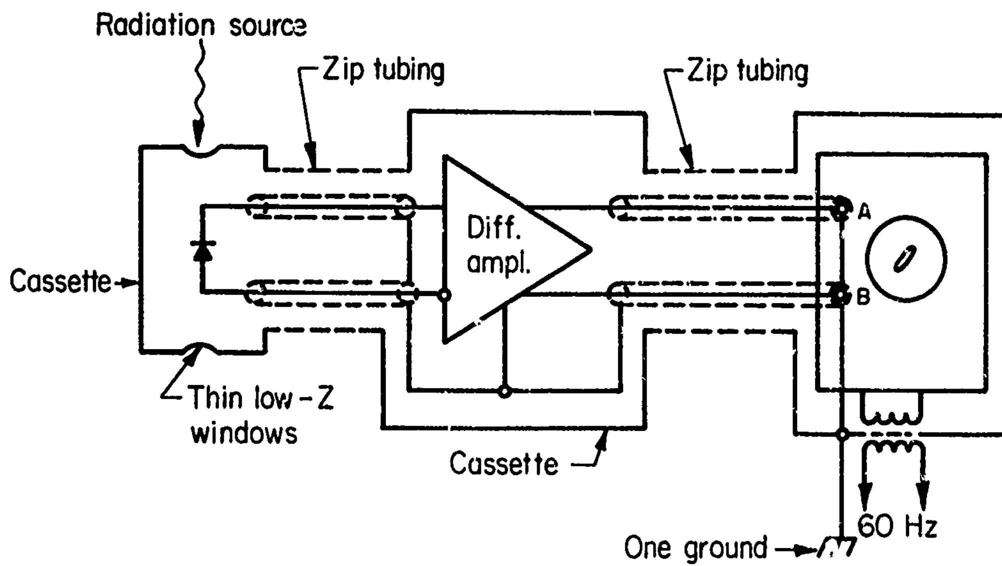


FIGURE 2.3. IMPROVED EXPERIMENTAL SETUP

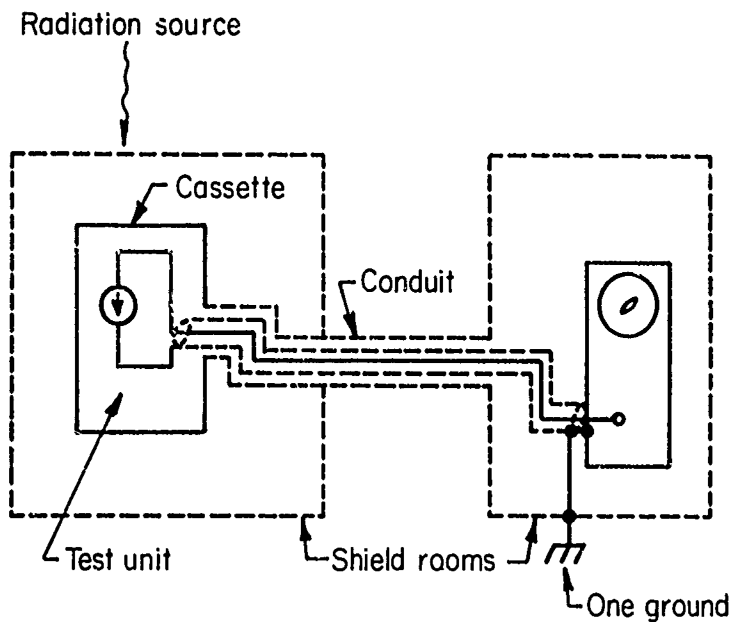


FIGURE 2.4. TYPICAL USE OF SHIELD ROOMS

Sometimes it is necessary to connect a number of pieces of equipment together – e.g., bias supplies, checkout equipment, and number of recording devices. Generally, these items will be capacitively coupled to their environment, even though they may be deliberately isolated from earth. The prospects of multiple-capacitive ground loops is then serious. An effective approach is to layout the instrumentation system along a ground plane, taking care not to introduce loops between the plane and the equipment and cables. Low-inductance coupling of the units in the plane (e.g., bolting racks together) is important. In this case, the cabling system to the test unit is looked at as an extension to the ground plane. Allowing cables to take two different routes from the recording station to the test unit would be a violation of the ground plane principle.

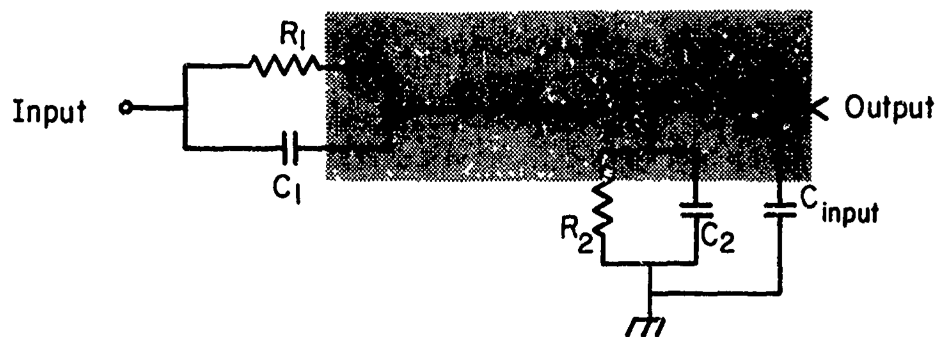
If noise is being injected into the system through the 60-Hz line, a well-designed filter or an isolation transformer may be sufficient to suppress the noise. In cases where these solutions fail, a motor-generator set with a low-capacitance insulated mechanical coupling should be used.

Cables used to periodically monitor conditions of the experiment in the exposure room, but not part of the active measuring circuitry, should be disconnected prior to taking data. These cables act as additional antennas and pump noise into the system. When required, they can be connected via relays or switches. Cables used to operate remotely controlled relays, motors, etc., should be carefully filtered at the point where they penetrate the experimental enclosure.

Circuit Considerations

Transmitting high-frequency signals over long coaxial cable runs between the exposure room and the instrumentation room requires that the cables be properly terminated in their characteristic impedances. In many cases, there is a mismatch between the experimental equipment and the cable. Therefore, some impedance-matching method must be employed, such as a cathode follower; or, if the signal is large enough, a simple voltage divider network may suffice. Care must be taken in the design of impedance-matching devices to insure that they faithfully reproduce the desired signal and that they are not susceptible to the radiation environment, contributing erroneous signals to the measuring circuits.

Simple resistive attenuators can be constructed which have input impedances of approximately 10 times the impedance of the cable used to transmit the signal. These are simple, have good frequency response, and low capacitive loading. Higher attenuation is generally not used because of increased sensitivity to replacement currents. Figure 2.5 shows a schematic of a passive attenuator probe. Generally a coaxial cable or printed-circuit stripline is used between the two resistors in the attenuator (shaded region in Figure 2.5). The replacement current which occurs in this shaded region will develop a voltage across the attenuator output. Attenuators with high resistances are more sensitive than low resistance attenuators.



For Proper Transient Response, $R_1C_1 = R_2(C_2+C_{input})$

Input Resistance $= R_1+R_2$

$$\text{Input Capacitance} = \frac{C_1(C_2+C_{input})}{C_1+C_2+C_{input}}$$

FIGURE 2.5. PASSIVE ATTENUATOR FOR VOLTAGE MEASUREMENTS

In measuring currents, the choice of series resistance is important. For the highest frequencies, current probes can be used. They have low insertion impedance, operate into terminated 50-ohm cables, but rather low sensitivity (~1 V/amp) and do not operate well at lower frequencies. If higher sensitivity is required, a series resistor is useful, but at a cost in insertion impedance and frequency response. For example, with a very low-capacitance preamp (~20 pF) the rise time across a 1-kΩ resistor is 20 ns. If the 1-kΩ resistor is connected with 3 ft of coax cable to the preamp, the rise time would be almost 100 ns.

In general, electronic circuits necessary for signal conditioning near the radiation exposure area should utilize vacuum tubes rather than semiconductors, since vacuum tube circuits can be made to show less sensitivity to the radiation. If semiconductors are to be used, extreme care must be taken to insure that the circuits are well shielded from the radiation and that any perturbations resulting from these circuits are at least an order of magnitude below that expected from the test sample.

Coaxial cables must be used with care in a radiation environment since they are also susceptible to the radiation and can produce large unwanted noise signals. Where it is necessary to use coaxial cable in the exposure area, it should be kept to a minimum length, with coils or loops of cable avoided. In some cases, where noise is repeatable from one radiation pulse to the next, methods of subtracting out the noise can be used. However, with coaxial cables, many types exhibit a radiation response which is dependent on the voltage and radiation history of the cable. Air-dielectric coaxial

cables are especially guilty of this type of response and therefore should be avoided. Solid-dielectric types with low capacitance per foot are preferable.

The most effective way of eliminating spurious currents due to the cables is by careful collimation of the beam and by proper shielding to prevent them from being irradiated. By these techniques, it is usually possible to reduce cable currents to negligible values in LINAC and flash X-ray tests.

Component cabling at a pulsed-reactor facility, however, must extend up to the machine, so that a portion of the cable is always irradiated. The signal produced in the cable during the reactor pulse may have little or no reproducibility for subsequent pulses. Whether the cable response will normally take a direction in accordance with the polarity of the applied signal appears to be influenced by the type of coaxial cable used and the magnitude of the applied voltage. There are no good recommendations for reducing or eliminating cable effects except that, after a number of pulses (three or so), the irradiated cable is more predictable. Since there is no method known at this time that will eliminate cable effects, the experimenter must conduct background experiments to determine the extent of the cable effects in the system he is using.

Another source which can affect the quality of the data is the response time of the measuring equipment. If the response time of the test circuitry is approximately the same as the radiation pulse width or the relaxation time of the irradiated test specimen, the resulting signal is not a true representation of what the signal would have been if the measuring circuit had not been connected. As a rule of thumb, the measuring system should have a response time at least a factor of ten faster than the relaxation time of the test sample, if the experimenter requires the signal to be reproduced with less than 1% distortion. Another alternative is to integrate the signal. For this type of measurement, the integrating circuit should have a time constant at least a factor of three longer than the sample relaxation time. Longer integrating time constants will improve data quality.

Practical Approach

In a particular experiment, the design must take into account the foregoing noise sources and minimizing techniques, weighed with the requirements of the experiment, and select the best approach. If in doubt, the safer approach from a noise standpoint is best, because the problem of noise-hunting at a large radiation facility can become very serious. Experiments have been performed at the largest flash X-ray facilities with noise levels of only a few millivolts. On the other hand, observations of noise signals of tens of volts have also been made. In between these bounds fall most experimental needs. As a general rule, high-frequency measurements ($\gtrsim$1 MHz) require much more care than low-frequency measurements ($\lesssim$10 kHz).

The facility to be used to perform transient radiation effects experiments will give an indication as to the degree of difficulty an experimenter can expect to encounter. Field tests are probably the most demanding, if only because the experimenter gets only one opportunity to obtain his data. Therefore, to participate in field tests (assuming one is making active measurements), the most stringent attitude should be taken regarding all the aforementioned methods of noise minimization. It may become apparent after the test that a more liberal approach would have sufficed, but the extra effort is cheap insurance compared to the loss of the total experiment if the noise proves to be excessive and obscures the data.

Flash X-ray experiments fall in the same general category as field tests, as far as noise problems are concerned. However, the experimentalist does have the luxury of taking "practice" shots to determine if his data is acceptable. This is time-consuming and expensive, and should be avoided if possible. Generally, flash X-ray facilities are provided with screen rooms and with well isolated 60-Hz power sources. A good practice is to apply the same philosophy in flash X-ray experiments as in field tests to obtain good signal-to-noise ratios and to minimize experimental problems.

Linear accelerators do not pose as difficult a problem as the previous two test facilities. The main noise problem at linear accelerators is due to RF noise getting into the measuring system. Therefore, if the experiment is contained in a good RF shield, this problem is usually minimized. Also, since the RF noise is systematic, a background measurement can be made and subtracted from the desired signal. However, good grounding and shielding techniques should still be observed in conducting LINAC tests.

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3.0 DOCUMENTATION REQUIREMENTS

3.1 INTRODUCTION

The inherent, unstated objective of any report should be to make clear to the reader the value and accuracy of the information contained in it. The entire effort of an expertly conducted experiment can be nullified if time and space is not taken to report the experiment in a manner that can be critically evaluated – by indicating the way in which the experiment was planned and performed, how the data were analyzed, and establishing a basis for the conclusions reached.

This section covers the general information normally required in a radiation-effects experimental report. No attempt is made to detail all the specific information that may be required; certainly a good deal of judgment in this regard is required of the report writer as he assesses his particular test circumstances. However, some of the following sections do point out many minimum specific details that normally should be reported.

It is assumed that the experimentalist preparing the report is familiar with technical writing and the typical structure of a technical report. Excellent discussions of good practices for preparing such reports are given in the bibliography. Occasionally the sponsoring agency will have a standard report format that must be followed. In all cases, however, the report should contain clear statements of the experimental purpose(s) and experimental objectives, a description of what was done and how it was done, and a concise but complete presentation of the test results and conclusions. Adequate information is particularly important in areas discussed below.

3.2 PLANS AND PROCEDURES

The objectives of the experiment and the planned method of obtaining these objectives should be briefly but completely described. Items to be included are:

(1) A brief statement – with references if necessary – of any theory pertinent to the experimental design, including any assumptions made and their justification

(2) A description of the experimental technique and apparatus, including circuits utilized in making measurements, special equipment fabricated for the experiment, and the accuracy and date of calibration of all test equipment (photographs and diagrams are helpful in this respect)

(3) Any precautions taken to assure the accuracy and precision of measurements, including precautions taken to exclude or limit extraneous variables

(4) A description and justification of any deviations from the experimental design, the causes thereof and remedial measures taken

(5) A description, with an example if necessary, of how the raw data were converted to the form used for analysis.

As discussed in Sections 2.1 to 2.3, a properly documented pre-test plan or test design will include most of the elements of the final report.

3.3 EXPERIMENTAL SAMPLES

All basic types of samples should be described. A good technique to follow is to prepare a distinct report section that, for the various types of samples, presents the manufacturer, type or specification number, lot number, origin (factory, distributor, etc.), the number of samples in each category, and method of selection and validation. If useful structural information (such as transistor emitter areas) is available, report it to facilitate data comparisons and to increase the general utility of the data. The importance of this information cannot be overemphasized. Include as an appendix any specification by which parts were selected or have a reference to where such data are available. In addition, any pertinent information about the history of the sample before irradiating it, such as previous exposure to radiation, must be noted. Sections 6, 7, and 8 include standardized formats for reporting data on the samples.

3.4 SAMPLE CONDITIONS DURING MEASUREMENTS OR IRRADIATION

The operational state of the samples and the nonradiation environmental conditions that the samples were exposed to from the time the samples entered the program until the last measurement was made should be defined in the report. Specifically, this includes such items as electrical operating point; temperature during irradiation, annealing, and measurement; mounting configuration and sample orientation with respect to the incident radiation; dosimeter positions; a description of any potting used; etc. Photographs of equipment setups, mounting fixtures, etc., are recommended.

3.5 RADIATION ENVIRONMENTAL DESCRIPTION

Documentation of TREE dosimetry should be clear enough so that another experimenter (1) can repeat the measurements and perform the same analysis, and (2) can apply the environmental description to another effect with possibly a different energy dependence to make response predictions. This implies that the reporting should specify what was actually measured, how the dosimetry values reported were obtained from the measured dosimetry data, and also any assumptions made in data processing. Section 5.7 treats documentation of the environment in more detail.

3.6 TEST RESULTS

General Requirements

The test results are the most important part of a report. They are the reason the experiment was performed. It is essential that they be reported as clearly and explicitly as possible. To make the report more comprehensible the results are usually presented in a condensed tabular or graphical form in the main part of the report. Even so, all of the basic (raw) data should be documented either as an appendix to the main report or in a separate report. Suggested formats for recording data are given in Sections 6, 7, and 8. Use of these formats will assist the experimenter in remembering to take all the necessary information and will put the data in a standardized form more readily usable by others. Charts, curves, and graphs are normally very helpful and desirable, but they should only supplement, not replace, basic data tabulations.

In planning an experiment, a theoretical model is usually selected to predict the effect to be expected. The reduced form of the data should then be chosen on the basis of the theoretical model, to reflect the expected dependence upon the relevant parameters. For example, first-order theory says that $1/h_{FE}$ of a transistor should increase linearly with fluence, independent of the initial value of h_{FE} for a given base width. Therefore, for a given transistor one should plot reduced data of $1/h_{FE}$ versus fluence. An even further step would be to observe that for a variety of base widths, but fixed base resistivity, a curve of $\Delta 1/h_{FE}$ versus Φ/f_t should be universal. Therefore, if one is trying to simplify the data presentation for a larger class of devices, such a plot should be used.

A measurement set is defined as the data taken on a group of samples of the same type (for example, the 2NZZZ transistor of Brand X) in a given combination of test conditions, such as fluence, electrical operating point, temperature, and radiation conditions. It is essential that, when the data

for a measurement set are presented, all qualifying test conditions be given specifically. If a reported quantity was not being measured directly, the method of analysis or evaluation should be given.

Tables and Figures

Each individual sponsoring agency may have a standard format for scientific and technical reporting including standard formats for tables and figures. A few are listed in the bibliography. The following suggestions are intended as a supplement to standard formats to aid in making more effective presentations.

Each figure should be as simple and bold as possible, and yet be meaningful without reference to the text. The abscissa and ordinate labels and the figure's title should clearly and concisely describe the figure in terminology consistent with that used in the text. Generally, curves are used to show trends or to compare sets of data, hence complete cross hatching of the figure with grid lines is unnecessary. If tic marks are used to indicate subdivisions, the meaning of the tic marks (value of the subdivisions) should be clear. The tic marks should go all the way around the margin of the figure.

Do not overcomplicate the figure by trying to make one figure do the job of two or more figures. If a figure is meant to represent a collection of data, show enough data points to adequately represent the degree to which the given curve fits the data. If error bars are used, state in the figure what they represent, i.e., standard deviation, range, etc. All independent variables for the data being described should be given with each figure or table. Whenever possible, orient figures and tables in the text in such a manner that the text does not have to be rotated to examine the figures.

3.7 ANALYSIS

A statement should be given as to the constancy of any control samples used. The estimated uncertainty in all important results should be quoted. In specifying errors, the value of one standard deviation is the quantity preferred, although other methods may be used if they are more suitable and are unambiguous. When statistical characterizations are given, at least a reference should be cited which explains the techniques involved.

In summary, a good experimental report is one which describes all the essential features that must be known to duplicate the test. Again, a majority of this information should be available from a good experimental design, as described in Section 2.2.

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4.0 RADIATION FACILITIES

4.1 SCOPE

This section presents a brief survey of the radiation sources used in TREE research and gives some general guidelines for source selection. Several classes of radiation sources are omitted from consideration because they fall outside the scope of the preferred procedures of Sections 6, 7, and 8. The guidelines given are general and should be used only in conjunction with the needs outlined in Sections 6, 7, and 8, as appropriate.

Only general characteristics are described for the radiation sources that are mentioned. Information on the specific characteristics of a particular machine and its associated facilities is best obtained firsthand from the operator of the radiation facility being considered, or from DASA 2432, TREE Simulation Facilities. The value of the latter document cannot be overemphasized. Time spent in examining the data given in it will greatly enhance the novice's understanding of the capabilities of the different classes of radiation sources most frequently used in TREE testing.

Recommendations for choosing certain machines from a given class of radiation sources are not made. The final choice of the particular facility to be employed rests with the experimentalist, who must make that choice after careful consideration of data requirements, cost, and convenience. Once an experimenter has tentatively selected a source, it is important that he contact the facility operator (preferably by a scheduled visit) early in the planning stages of a test. Each facility has unique characteristics and restrictions; in fact, these frequently determine the basic structure of a test plan. To intelligently select a facility or plan a test, the experimenter must understand the basic phenomena with which he is dealing. The reader is referred to Section E of the TREE Handbook and to basic nuclear physics texts on radiation interactions.

4.2 GENERAL CHARACTERISTICS OF RADIATION SOURCES

From a machine designer's viewpoint, radiation sources are considerably different within each class, but from the operational viewpoint of the experimenter, different sources within a class have many characteristics in common. The common characteristics of several important classes of radiation sources are discussed in the following text.

Nuclear Reactors

For TREE testing considerations nuclear reactors may be divided into two operational modes: the steady-state mode in which the reactor operates at a relatively constant power level for relatively long periods of time and the pulsed mode in which the reactor can be pulsed to a high power level for times much less than 1 second.

The radiation parameters associated with pulsed and steady-state reactors vary widely. However, common features may be noted. Gamma dose rate and fast- and slow-neutron fluences are the parameters of primary interest in radiation-effect experiments. They are determined by the reactor power level and by the pulsed-reactor pulse width or by the time of irradiation at a steady-state reactor. Very grossly, the gamma dose rate induces photocurrents in electrically active devices, fast neutrons induce permanent damage, and thermal neutrons are primarily responsible for inducing radioactivity in test samples. Actually, either directly or indirectly, each type of nuclear particle or radiation can produce each type of effect.

Normally, the absolute intensities of the gamma, fast- and slow-neutron fluxes are well known for the normal sample positions in reactors. However, some samples can create significant perturbations in the reactor spectra, thus inducing an error in the "known" spectra. In addition, any changes in the core configuration or insertion of other materials in the reactor, particularly the core, can alter the spectra. It is always wise to consult with the facility's technical staff to determine the accuracy of the dosimetry information provided by the facility and to make sure that it represents the current state of the reactor. As a further safeguard, always determine at least the S/Pu ratio to check the reactor's spectra.

Radiation-induced heating of the sample is of concern in some instances. The heating rate is related to the rate of energy deposition from both neutrons and gamma rays and can be calculated by personnel at the radiation facility. As a rule of thumb, provision for cooling the sample may be required when operating in an air void in a steady-state reactor operating at a power level near or above 30 kW. The degree of temperature control required depends on the device parameter involved and the end use of the data.

Thermal neutron shielding of samples inserted in a reactor may be required to limit the formation of radioisotopes in the materials of the experiment. Typically, an experiment will be surrounded or wrapped in a 0.040 inch thick cadmium foil.

All nuclear-reactor facilities require in-house clearance of experiments before the experiments can be performed at the facilities. All facilities will supply dosimetry services upon request. Experiment preparation may require

a time of up to 2 months before a test may be performed. Test schedules should be made accordingly.

For more definitive descriptions of several pulsed-reactor facilities, see DASA 2432, TREE Simulation Facilities. This document also contains lists of other pulsed and steady-state reactors in the United States.

Pulsed-Mode Reactors

Pulsed-mode reactors are of two types, air cooled and water cooled. These reactors can also be operated in a steady-state mode, but steady-state operation of some air-cooled reactors is discouraged because they produce large fission-product inventories in the reactor core.

The air-cooled reactors are suspended or sit on tables to provide easy access at a convenient height. Water-cooled reactors are generally suspended in a pool of water about 20 feet below the water surface. The volumes of reactor cores vary between about 1 and 10 ft^3. When operating, they produce a neutron and gamma-radiation field in their vicinity, the intensity of which is proportional to the reactor power level. It is possible to suspend test samples in the core of some reactors to maximize the radiation intensity. However, in-core irradiation is usually limited to small samples, and the number and type of dosimetry foils that may be used also is limited. Test samples also may be placed at a variety of locations outside the core of both reactor types, resulting in a wide range of radiation intensities.

Pulsed-reactor facilities are frequently used for neutron/gamma transient-radiation-effects studies and, along with steady-state reactors, are used for permanent neutron-damage studies.

Care must be taken not overlook the possible ionization effects of neutrons when performing a test at a pulsed reactor. Usually the ionization is predominantly a gamma-radiation effect, but neutrons also are efficient ionizers in materials with low atomic numbers. The ionization dose produced by neutrons in silicon is of the order of 3×10^{-11} rads (Si) per n/cm^2 ($E > 10$ keV, Pu, fission). (For 14 MeV monoenergetic neutrons, the value increases to 3.3×10^{-10} rads (Si) per n/cm^2.)

Since reactors must be pulsed by a licensed operator, remote pulsing by the experimenter is not allowed. The experimenter is given either an electrical signal or a countdown to start the recording instrumentation.

Steady-State-Mode Reactors

There are numerous steady-state reactors in use in all parts of the world for experimental purposes. These reactors vary considerably in design and available neutron flux. They are used basically as a source of neutrons.

The principal use of steady-state research reactors (and pulsed reactors operated in the steady-state mode) in TREE work is for neutron permanent-damage studies of components. These reactors may often be cost effective for permanent damage tests of components.

A listing of such reactors in the United States is given in TREE Simulation Facilities, DASA 2432. The experimenter contemplating the use of such a reactor should contact the facility's operator concerning the availability and applicability of the reactor.

Electron Linear Accelerators (LINAC's)

In an electron linear accelerator (LINAC), high-energy electron beams are produced that are useful in TREE studies, both directly and after conversion to bremsstrahlung photons or to photofission neutrons. LINAC's are widely used as a pulsed radiation source in TREE studies because of their controllable variable pulse length, intensity, and particle energy.

Direct LINAC electron irradiation is used to produce ionization at higher dose rates than can be obtained with bremsstrahlung. The electron beam can be used directly and focussed on a small item such as a transistor to obtain doses approaching 10^{12} rads (Si)/s. The desired high dose rates are accompanied by the problems of replacement current and secondary emission from surfaces, but these problems are usually resolvable by careful experimental design. For lower rates, or for larger test item sizes, a bremsstrahlung target may be used. Energies as low as a few MeV up to many tens of MeV are available in various radiation effects LINAC's. Dose-rate variation is obtained by use of scattering foils, by backing the test away from the LINAC beam port as needed, or by defocussing the beam within the machine.

Neutrons can be generated by a LINAC via the photofission process, in which photons of energy above about 5 MeV are incident on a U-238 target. However, due to the shape of the bremsstrahlung spectrum and the variation with photon energy of the cross section for the reaction, the LINAC should be operating with at least 25-MeV beam energy for higher efficiency.

The LINAC is a valuable tool for the study of radiation effects because of the following characteristics:

- Through the use of the direct electron beam, dose rates above 10^{11} rads (Si)/s can be obtained.
- At many facilities the pulse width and dose rate may be independently varied over a wide range without changing sample position or test configuration.
- Single or multiple pulses are normally available on command.
- Short rise and fall-time pulses are the normal operational characteristics.
- Conversion from electron to gamma radiation is readily accomplished using a bremsstrahlung converter (although the converter will have a secondary electron output, also). The bremsstrahlung dose rate obtained will be at least a factor of 100 less than the direct electron dose rate.
- The LINAC may be used to produce fast neutrons by the photofission process in a suitable target, typically depleted uranium.

The major disadvantage in using the LINAC is the restriction imposed on sample size when the electron beam is used directly. Most other disadvantages are normally experiment oriented, e.g., the dose rate obtainable may be too low or too high for a particular application.

In practice, there are several practical considerations to be noted when performing tests at a LINAC. The major considerations are listed below:

- Peak current is achieved at energies somewhat less than the maximum energy.
- Minimum beam diameters (affecting peak dose rates and maximum sample size) are in the range 0.2 to 2 cm at the beam exit window.
- In air, the beam diameter expands approximately linearly with distance from the beam exit window; this implies an inverse-distance-squared dose-rate dependence. The angular spread of the beam varies from facility to facility.
- When testing at any pulsed accelerator, good RF shielding is necessary in the form of shielded boxes to house the experiments, double shielded cables, and careful and proper one-point grounding. Also, if line drivers are used, care should be taken that neither RF noise nor radiation-induced signals mask the desired signals.

- Multiple entries to the target (sample irradiation) area are time-consuming and therefore expensive. An average of 5 min per entry is typically required when only minor changes in test configuration are made. A remotely controlled sample change should be considered for many sample irradiations having similar geometries.
- Protection of the samples irradiated in the direct electron beam may be required during retuning of the LINAC. (This is not as serious a problem as with a FXR, but it is likely that the first shot after the LINAC has been shut down for a few minutes will be different due to slight detuning. Hence, on "single pulse" mode, active monitoring of radiation at the sample is recommended.) The dose delivered to test samples during tuning must be measured and considered in the data analysis. Significant sample heating also can occur.
- Placement of dosimeters with respect to samples must be planned such that the dosimeters will accurately measure the dose received by the sample without causing a large nonuniformity in the test-sample dose.
- Beam current-density profiles may change considerably during a long experiment. Effective pulse-to-pulse monitoring of the beam must be included in the dosimetry plans for a test.
- A system for locating the beam prior to sample placement is required. Collimators and monitors are in common use for beam location and monitoring. Also, polyvinylchloride (PVC) plastic sheets, which darken after irradiation to between 1 and 10 Mrads, have been satisfactorily used for this purpose. If a remote television monitor is available at the facility, it is possible to observe scintillations in many plastics as the beam passes through the plastic, and thereby check beam stability as machine parameters are varied.
- It is quite normal to achieve an average of 5 to 6 useful machine hours of operation per 8-hour working day during a test lasting several days.
- The characteristics of several LINAC's are described in detail in DASA 2432, TREE Simulation Facilities.

Flash X-Ray Sources

"Flash X-Ray Machine" is the designation generally applied to that class of machines which generates an intense pulse of X rays (bremsstrahlung) by conversion of electrons produced by discharge of stored electrical energy through a cold cathode tube. These machines also are used as electron-beam generators since the electrons can be used directly for

irradiation studies. Flash X-ray sources differ from linear accelerators in that the electrons are accelerated by an intense pulsed electric field rather than an RF field. By varying many machine design factors such as stored charge, electron energy (accelerating voltage), circuit parameters, cathode geometry, and target material, a wide range of bremsstrahlung intensities, energies, and beam spatial-distribution profiles may be obtained. However, for a given machine, the pulse width is essentially fixed, and only limited variations in photon energy and dose rate are possible.

Various commercial flash X-ray machines produce bremsstrahlung with photon energies varying from 150 keV peak to several MeV peak, the peak energy corresponding to the electron accelerating voltage. The larger flash X-ray machines are frequently referred to as super (SFX) or advanced (AFXR) flash X-ray machines. These larger flash X-ray machines can usually deliver very high dose rates over large volumes. The bremsstrahlung energy distribution is such that the spectrum maximum occurs usually at less than one-third of the peak energy.

The spatial distribution of dose rate during the pulse generally looks like a "dipole gain lobe". The lobe pattern will vary from burst to burst at short distances from the source; it may even switch from single to multiple lobes during a burst, although this can be minimized by careful machine operation. Thus, the effective bremsstrahlung-source location can change slightly. This effect will often become apparent when dosimetry "beam maps" are performed. Very often a dosimeter beam map close to the target will show large peaks or valleys in close proximity to one another. This effect is usually not noticeable a few feet from the source where multiple lobes are homogenized.

The beam-switching phenomenon is only of concern when testing within a few feet of the target and only when the time history of the burst (pulse shape) is of importance. Many devices do not respond in direct proportion to the pulse amplitude (i.e., their response is not an equilibrium response). For these devices, only the prompt dose (not dose rate) is important; the dosimeter result (total dose measurement) is adequate. Where the pulse shape is required and when testing close to the target, the pulse shape detector must be placed directly at the test sample.

At a flash X-ray source, the energy distribution (spectrum) is a function of time since it requires a finite time for the electron accelerating potential to reach a maximum and to decay to zero. X-ray source configuration, sample packaging, and material in the vicinity of a test sample will cause the photon energy spectrum to vary with location. The spectrum will also differ at various points in a plane perpendicular to the beam direction due to nonuniform absorption in the target material. The magnitude of the fluorescent X-radiation from the target is virtually unknown. In addition, each of these factors may change significantly over the life of the

X-ray tube. For all of the above reasons, the spectra available for individual flash X-ray machines are likely to be only rough approximations of the photon energy spectra; further, changes will occur over a period of time.

The pulse width can be varied slightly on some of the high-energy machines, but it is not a simple procedure. The pulse shapes are roughly gaussian or triangular, and the total pulse width is usually more than twice the width at half-amplitude. On some higher energy machines the cathode configuration can be changed. This alters both the beam half-angle and the distance between the effective origin of the burst and the closest possible sample position (although this distance is often about 2.5 cm).

Since the mass-energy absorption coefficients increase drastically at energies less than about 100 keV for low-atomic-number elements like silicon, it is at sources that have significant low-energy components (especially, the low-energy flash X-ray machines) that environmental correlation is most difficult. Lower energy components deposit their energy near the front surface of the test item, resulting in a very nonuniform dose throughout the material. For this reason, it is generally advised that filters be used (see "Spectral Filtering" in Subsection 5.5) to suppress the low-energy components to the greatest degree practical. Some concern has also existed that, even at sources operating at high nominal energies, there may be a significant low-energy component present due to photons or electrons that have been degraded in energy by scattering. Although some test results indicate that this effect is probably very small, it is nevertheless good practice to eliminate any unnecessary scattering material from the vicinity of the sample.

Radiated noise from the machine and surrounding objects will usually be a serious problem at larger flash X-ray facilities and will be different at each facility and for every instrumentation system. Therefore shielding will have to be tailored to meet the requirements of each test and design should be flexible enough to permit on-site modifications. At facilities having larger flash X-ray machines, double or triple shielded transmission lines about 40 feet long are usually required and the test items must be enclosed in an RF shield. Low-energy flash X-ray machines are usually small enough to make it more practical to enclose the noise radiating portions of the machine in an RF shield.

Another consideration for the instrumentation system is command pulsing of the X-ray machine by the user. Most machines are equipped with this feature which allows the timing of the occurrence of the X-ray pulse with some event in the test sequence. Although limitations of this feature will differ at each facility, it can be expected that there will be a fixed delay time – the pulse delay will have some uncertainty (the timing jitter) between the command signal and the occurrence of the X-ray pulse.

Detailed descriptions of several flash X-ray facilities are given in DASA-2432, TREE Simulation Facilities.

Miscellaneous Sources

Various radiation sources other than those already discussed in this subsection are used sometimes in TREE studies. Among these are radioactive isotope sources, spent fuel elements from nuclear reactors, steady-state particle accelerators, and high energy neutron sources.

Isotopes

Radioactive isotopes are useful as calibration and standardization tools, since they generally have well known half-lives (and therefore knowable specific activities) and decay schemes (and therefore known radiation types and energies). Co-60 decays with a half life of 5.3 years, emitting two gamma rays per disintegration of energy 1.17 and 1.33 MeV. One sees a dose rate of 4.1×10^{-3} rad (air)/s, per curie, at 1 ft from a small source of Co-60. Practical irradiation sources have activities of from 1 to several hundred thousand curies. Although isotope sources cannot be used for high-dose-rate simulation, they may be useful and economical for irradiation to high total doses when rate effects are not important or as a source for low-rate radiation-effects studies. Examples of TREE research in which Co-60 irradiation is useful are found in studies of surface effects and equivalence of radiation exposures for permanent bulk damage.

Spent fuel elements can also be used as a source of gamma radiation. Fuel elements from a nuclear reactor always contain a significant buildup of gamma ray emitting radioactive isotopes after they have been in a reactor for a period of time. Hence, these elements also can be used in instances when low dose rates or total dose are of interest. The dose rate available from a spent fuel element varies according to its type, its reactor history, and the length of time that it has been out of the reactor. The gamma-ray energy spectra from spent fuel elements is mixed and varies with time; however, the average energy will be about 0.7 MeV.

14-MeV Neutron Sources

When a deuterium ion (d) with an energy of a few hundred keV collides with a tritium ion (H^3), a fusion reaction occurs in which a helium ion and a 14 MeV neutron are the end products. Machines are available which utilize this reaction to produce neutrons. One type machine (Kaman Nuclear) produces this reaction by accelerating deuterium and tritium ions into a tritium impregnated titanium target. In another method (the AFWL/SAMSO coaxial plasma source at Physics International) for producing 14 MeV neutrons, a tritium-deuterium gas mixture is ionized and compressed in a 500 kJ coaxial plasma gun to form a dense plasma focus within which the $H^3(d,n)He^4$ fusion reaction occurs.

The Kaman Nuclear machines are designed for continuous operation (up to 100 hr) and produce a maximum neutron flux for small samples (e.g., TO-18 transistor package) of 2×10^{10} n/(cm$^2\cdot$ s)(E $\approx$ 14 MeV). The absorbed dose from these machines due to neutron ionization and scatter gamma rays amounts to about 1.2×10^{-9} rads (Si) per 14 MeV n/cm^2. The machine produces negligible RF noise and typically requires cable runs of 20 feet from accelerator to control unit.

The Physics International machine operates in a pulsed mode producing a fluence of 1×10^{11} n/cm^2 over a 1.125 in. diameter test area with a pulse width (FWHM) of 10^{-7} s. The minimum pulse interval is 5 minutes and the working rate is 20 pulses per day. A synchronizing pulse from the control console is provided, or the machine can be pulsed by the experimenter. The pulse jitter is comparable to that of a high energy flash X-ray machine (±100 ns). Single shield RF protection is provided in the screen room with ground plate extended to the test area. A cable run of about 40 ft is necessary to get from the screen room to the test area.

Direct-Current Accelerators

Van de Graaff, Dynamitron, and other such accelerators are used to produce controlled-energy particles in TREE work for neutron permanent damage and high dose research and for calibration work. Longer pulses of electrons or neutrons can be made than are readily available at a LINAC or other sources by switching the beam on and off, or by sweeping it magnetically past an experimental item. Electron irradiations using a dc accelerator provide a means of high dose or high-rate exposure.

Typical reactions used in these accelerators to produce neutrons include Be^9 (d,n) B^{10} for neutrons in the 0.5-6 MeV range and H^3(d,n)He^4 for 14-MeV neutrons. Target cooling problems go hand-in-hand with increased beam current and flux and may pose an experimental design problem in obtaining desired flux over designed volumes at positions near the target.

Typical neutron fluxes per milliampere of beam current which are obtainable are 5×10^{13} n/(s$\cdot$ steradian$\cdot$ mA) from the H^3(d,n)He^4 reaction and 1.5×10^{11} n/(s$\cdot$ steradian$\cdot$ mA) from the Be^9(d,n)B^{10} reaction. This leads to total useful energetic neutron fluences on the order of 10^{13} n/cm^2 over an area of a few square centimeters in times on the order of 1 min for the H^3(d,n)He^4 reaction and times on the order of 2 hr for the Be^9(d,n)B^{10} reaction while operating at 1 mA of positive ion current. High currents over extended periods of time are practicable; however, good target cooling is necessary to avoid target material depletion.

In working with dc accelerators care must often be taken in measuring the small currents involved. Electrometers and current integrators are

used, and good insulators, guard electrodes, and other such techniques are usually needed.

4.3 SOURCE SELECTION

Some of the major features of various radiation sources were briefly mentioned in the last section. The characteristics of radiation facilities that are desirable for typical TREE experiments are presented in this section. Because of the variety of experimental considerations involved, it is not feasible to "standardize" research nor to recommend unequivocally a single radiation source for use in TREE studies.

General Considerations

The need for simulation of a given radiation environment to produce a predetermined effect requires careful source selection. The obvious parameters to be considered are, of course, cost, radiation type (generally photons, neutrons, or electrons for TREE work), energy spectrum, and time dependence. Other considerations possibly less obvious at first glance but requiring consideration from a practical standpoint are listed below under Operational Considerations, though not necessarily in order of importance.

Within the scope of this preferred procedures document there are basically two types of device response of interest: transient response (typically photocurrents generated in the bulk material) and permanent response (damage either in the bulk or surface of the devices). The basic test-environment requirements for these responses are given below.

Transient-Response Considerations

Transient responses typically result from photocurrents introduced through ionization phenomena due primarily to photon irradiation. However, neutron ionization can also cause photocurrents of interest. Therefore in most cases, a pulsed source of ionizing radiation is desirable having: (1) rise and fall times short compared to diffusion times, and long enough and with controllable pulse-length capabilities to achieve equilibrium photocurrent in the device under test; (2) sufficient intensity to produce the required range of dose rates in the device (i.e., to obtain data both where I_{pp} is linear with dose rate and at the high rates where nonlinearities appear); (3) sufficiently energetic photons or electrons to penetrate the case of the device and produce a uniform dose throughout the active volume; (4) an

energy spectrum sufficiently well-known so that the dose rate in the active volume can be accurately determined by standard methods; and (5) spurious RF noise low enough to avoid confusion of effects. These are ideal characteristics and are not to be found in any one pulsed source.

Many LINAC's and flash X-ray machines closely approximate these criteria if proper precautions are taken. The LINAC has the advantages of variable and long pulse width and better-controlled beam diameter, position, intensity, and shot-to-shot performance. The flash X-ray has the advantage of a larger irradiation-volume capability for tests on several devices simultaneously.

There are two other transient responses of devices which can be of concern with some systems and which therefore need to be briefly mentioned. The first response results from short-term annealing of bipolar transistor gain. Because transistor-gain degradation is primarily caused by neutrons, a pulsed source of neutrons with sufficient fluence ($>10^{12}$ n/cm^2) and short duration (depending on response times of interest) is needed. The appropriate pulse width for characterizing this effect will depend upon the system specification to be applied to the part being characterized.

Second, a transient response attributable to surface effects has been observed in some devices. Sources of ionizing radiation with pulse widths that are short with respect to the response times of interest should be used to evaluate the influence of this effect on device response.

Permanent-Response Considerations

Permanent responses of devices are attributed to physical-property changes which can persist for long periods of time as compared to the measurement circuit response time. For this document, permanent responses can be grouped into two categories: bulk and surface effects. The bulk effects are due to lattice displacements in the bulk of the material induced by high-energy radiation, primarily neutrons. Surface effects are primarily due to ionizing radiation causing changes in the surface conditions of the bulk material. Therefore, for permanent-bulk-damage type of experiments, a neutron source is desirable having: (1) sufficient fluence of energetic particles at the experiment position to produce, in reasonable experiment times, the desired bulk damage; (2) a spectrum sufficiently well-known to allow characterization of the spectrum in standard terms by standard methods; and (3) a known neutron-to-gamma ratio that is high enough so that any effects due to the gamma radiation are negligible in comparison with neutron-induced effects.

Pulsed reactors, some steady-state reactors, and some accelerator-generated neutron sources meet these criteria. Accelerator-generated

neutrons may have the energy distribution of a fission spectrum if they are generated in the photofission process, or they may be nearly monoenergetic if a fusion reaction such as the $H^3(d,n)He^4$ reaction is used. There are also sources utilizing a plasma of deuterium and tritium gases which generate 14-MeV neutrons.

For permanent-surface-effect types of experiments, a source of ionizing radiation that produces a minimal amount of bulk damage is necessary. For electrons in silicon, energies less than about 150 keV meet this requirement. However, if the total dose is less than about 10^6 rads (Si), bulk damage is negligible and higher energy radiations may be utilized. Isotope sources, ion accelerators, LINAC's, and flash X-ray machines all can meet these criteria.

Operational Considerations

Once the test engineer has decided upon the type of radiation facility that he should use, the selection must be made of the particular facility which will permit him to attain his experimental objective with the resources at his command. The determining factors in this decision are the operational considerations. Operational considerations are those factors which can only be determined by the test engineer, usually after he has completed his experimental design. They depend upon such factors as the funds he has available, his own expertise as an experimenter in TREE effects, the physical dimensions of his experiment, and the accuracy and precision required to obtain his experimental objectives. At this time, a careful review of Section 2.5, Experimental Hardware Considerations/Techniques, may be helpful.

An obvious consideration is the cost of using the facility, including rental fees and transportation of personnel and equipment to the facility. This may be related to the support capabilities available at the radiation facility. Does the facility have a staff experienced in TREE testing available for consultation? How much assistance will the facilities staff be able to provide to the experimenter? Will adequate (quality and quantity) test equipment be available at the facility or will the experimenter have to provide it himself? What dosimetry services can the facility provide?

The size of the experiment with respect to the exposure area available must be considered. How uniform is the dose and/or dose rate at the location where the experiment will be performed, both across the front surface and from the front to the back of the experimental package? Are the energy spectrum and/or yield component ratio (n/γ ratio in a reactor, etc.) satisfactory?

The problems of remote operation – including long-cable effects, the possible need for precise test-sample positioning, or frequent setup change – must be considered. Can the radiation source be pulsed by a signal from the

experimenter – i.e., synchronization of the radiation pulse with an experimental equipment signal – or must the experimenter depend on a signal from the facility's operator? What will be the uncertainty in knowing exactly when the pulse will occur?

What precautions will be necessary to protect the experiment from unwanted noise at the facility under consideration? Will spurious signals, including charge scattering from the test fixtures and electromagnetic RF noise due to the radiation generator or the radiation itself, be more of a problem at one facility? Is a screen room available for the experimenter's use? Is it large enough for the experiment planned?

These considerations probably are not all applicable to any one experiment. They are not intended to be all inclusive but are meant to stimulate the experimenter's mind and start him thinking when attempting to select the best source for an application. The final decision must be made by the experimenter, keeping in mind the objective of his experiment and the resources that he has available.

A lead time of from a few days to a few months is usually necessary in scheduling a test at a facility. At many facilities, an experiment test plan must be submitted and approved before a firm scheduling commitment will be given. The experimenter should contact the facilities under consideration at the earliest possible time to determine these limitations and requirements.

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5.0 DOSIMETRY AND ENVIRONMENTAL CORRELATION

5.1 INTRODUCTION

Dosimetry is the process of measuring and providing a quantitative description of a radiation dose, preferably in terms relevant to the radiation effect being studied. In its most general form, the environment can be described by stating the (possibly time dependent) number of nuclear or atomic particles of various types and energies (the spectrum) which cross a given surface. It is not feasible economically to make such measurements, and such complete descriptions are rarely available. But, fortunately for most radiation effects experiments, they are not required. In mathematical terms, for a radiation spectrum $\phi(E)dE$ and a radiation effect with energy dependence $R(E)$ assumed to be time independent, the total effect produced by the spectrum is

$$R = \int R(E)\, \phi(E)dE. \tag{5.1}$$

For example, if a particular radiation effect of interest has a response, $R(E)$, which is fairly insensitive to energy over the energy range of interest (that is, if $R(E)$ = constant), then the total effect is just

$$R \cong \text{Constant} \int \phi(E)dE \cong \text{Constant} \times \Phi. \tag{5.2}$$

The integral in Equation 5.2, denoted by Φ, is just the total fluence, and the particular effect used as the example is one proportional only to the total fluence. Since this effect is independent of spectral shape, the total radiation fluence is the relevant quantity and is all that must be determined when describing the environment. On the other hand, if an effect such as neutron displacement damage in silicon (which is quite dependent on neutron energy) is being studied, the total effect is described by Equation 5.1, in which case both the total fluence and its energy spectrum are relevant and should be determined.

The measurement of a radiation environment also entails the determination of a radiation effect. In this case a dosimeter with a known response function $D(E)$ which has been calibrated with respect to the radiation field is used and a measurement

$$D = \int D(E)\, \phi(E)dE \tag{5.3}$$

is obtained. If the dosimeter response function, $D(E)$, is approximately proportional to $R(E)$ for the energy range of importance to these integrals, it is a fortuitously appropriate dosimeter. If it is not, other information, such as an estimate of the shape of $\phi(E)$, will be needed to relate the

dosimeter reading, D, to the expected effect, R. One measure of the appropriateness of a detector is measured, therefore, by how closely its response function is related to the response function for the radiation effect being studied for the type of radiation considered. This same conclusion applies to the appropriateness of a dosimetry unit, such as the ones defined under the following Definitions of Units subsection.

For example, it has been established that the magnitude of bulk ionization effects in silicon is a function only of the ionization energy deposition. Therefore, the appropriate unit for describing ionizing radiation when interested in ionization-induced currents in a silicon device is a unit of energy deposition in silicon, e.g., rad (Si). Any dosimeters whose reading can easily be converted to rad (Si) in a way which is not sensitive to the detailed spectrum of the incident radiation are then useful. By way of contrast, displacement effects in silicon represent a totally different response to the radiation spectrum, and the rad (Si) is an inappropriate unit. In this case the total fluence and spectral shape or the equivalent fluence of some energy or spectrum of neutrons which would produce the same concentration of displaced atoms in silicon [neutrons/(cm^2)-1 MeV equivalent or neutrons/(cm^2)-fission spectrum equivalent] is frequently used.

Perhaps the most common error made in a radiation effects experiment is to neglect the effect of the perturbation of the radiation spectrum created by the presence of the experiment. It is this perturbed spectrum and not the free field spectrum which should in principle be used in the correlation or in determining the total radiation fluence from a monitor dosimeter (or foil) used with the experiment. In many cases it is the zeroth approximation of the true spectrum, i.e., the free field spectrum, that is used.

Before proceeding with a definition of units and descriptions of dosimeters, it is appropriate to comment on two commonly used and misused terms: correlation and simulation. As applied to radiation effects, we define them as follows:

<u>Simulation</u> is the production of a particular radiation effect by any means.

<u>Correlation</u> is the establishment of the relative intensities of different radiation spectra or other types of stimulation required to produce the same effect.

Note that simulation does not necessarily imply any need to reproduce a radiation environment, only its effect. If the same effect can be produced by electrical or optical means rather than nuclear radiation, these are valid simulation techniques for that effect. Note also that the correlation between radiations must be established separately for each class of effect. For example, the correlation between different energy neutrons is much different for displacement effects than for ionization effects.

Definitions of Units

The Defense Nuclear Agency (DNA) has adopted as standard the definitions of radiation quantities and units in Report 11 of the International Commission of Radiological Units and Measurements (ICRU). The document is recognized as the principal source reference on standard radiation units. Several of the more important units and definitions are abstracted in the following paragraphs for convenience to the users of this document. Some units commonly used as a measure of various defined quantities are included.

(1) Directly ionizing particles are charged particles (electrons, protons, alpha-particles, etc.) having sufficient kinetic energy to produce ionization by collision.

(2) Indirectly ionizing particles are uncharged particles (neutrons, photons, etc.) which can liberate directly ionizing particles or can initiate a nuclear transformation.

(3) Ionizing radiation is any radiation consisting of directly or indirectly ionizing particles or a mixture of both.

(4) The energy imparted by radiation to the matter in a volume is the difference between the sum of the energies of all the directly and indirectly ionizing particles that have entered the volume and the sum of the energies of all those that have left it, minus the energy equivalent of any increase in rest mass that took place in nuclear or elementary particle reactions within the volume.

(5) The absorbed dose (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of the matter in that volume element.

$$D = \frac{\Delta E_D}{\Delta m} \text{ (ergs/g, rads, cal/g).}$$

(5a) Rad is a unit of absorbed dose. One rad is the absorption of 100 ergs/g of material being irradiated.

(6) The absorbed dose rate is the quotient of ΔD by Δt, where ΔD is the increment in absorbed dose in time Δt.

$$\text{Absorbed Dose Rate} = \frac{\Delta D}{\Delta t} \text{ [ergs/(g·s), rads/s, cal/(g·s)].}$$

(7) The particle fluence, or fluence (Φ) of particles, is the quotient of ΔN by Δa, where ΔN is the number of particles that enter a sphere of cross-sectional area Δa.

$$\Phi = \frac{\Delta N}{\Delta a} \text{ (particles/cm}^2\text{)}.$$

(8) The particle flux density, or flux density (ϕ) of particles, is the quotient of $\Delta\Phi$ by Δt, where $\Delta\Phi$ is the particle fluence in time Δt.

$$\phi = \frac{\Delta\Phi}{\Delta t} \quad \frac{\text{particles}}{\text{cm}^2 \cdot \text{s}} .$$

Note: This quantity may also be referred to as particle fluence rate.

(9) The energy fluence (F) of particles is the quotient of ΔE_F by Δa. ΔE_F is the sum of the energies, exclusive of rest energies, of all the particles that enter a sphere of cross-sectional area Δa (ΔE_F = kinetic energy per particle x number of particles with that energy).

$$F = \frac{\Delta E_F}{\Delta a} \text{ (calories/cm}^2\text{, MeV/cm}^2\text{)}.$$

(10) The energy flux density or intensity (I) is the quotient of ΔF by Δt where ΔF is the energy fluence in the time Δt.

$$I = \frac{\Delta F}{\Delta t} \text{ [calories/(cm}^2 \cdot \text{s), MeV/(cm}^2 \cdot \text{s)]}.$$

Note: This quantity may also be referred to as energy fluence rate.

(11) The exposure (X) is the quotient of ΔQ by Δm, where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons), liberated by photons* in a volume element of air whose mass is Δm, are completely stopped in air.

$$X = \frac{\Delta Q}{\Delta m} \text{ (R)}.$$

(11a) Roentgen (R) is the unit of exposure.

$$1 \text{ R} = 2.58 \times 10^{-7} \text{ C/g}.$$

(This unit is numerically identical with the old one defined as 1 e.s.u. of charge per 0.001293 gram of air. C is the abbreviation for coulomb.)

(12) The exposure rate is the quotient of ΔX by Δt, where ΔX is the increment of exposure in time Δt.

*For purposes of this document photons will be taken to mean any ionizing radiation.

$$\text{Exposure Rate} = \frac{\Delta X}{\Delta t}\ (\text{R/s}).$$

(13) The mass attenuation coefficient (μ/ρ) of a material for indirectly ionizing particles is the quotient of dN by the product of ρ, N, and dl, where N is the number of particles incident normally upon a layer of thickness dl and density ρ, and dN is the number of particles that experience interactions in this layer.

$$\frac{\mu}{\rho} = \frac{1}{\rho N}\frac{dN}{dl}\ (\text{cm}^2/\text{g}).$$

The term "interactions" refers to processes whereby the energy or direction of the indirectly ionizing particles is altered.

(14) The mass energy transfer coefficient (μ_K/ρ) of a material for indirectly ionizing particles is the quotient of dE_K by the product of E, ρ, and dl, where E is the sum of the energies (excluding rest energies) of the indirectly ionizing particles incident normally upon a layer of thickness dl and density ρ, and dE_K is the sum of the kinetic energies of all the charged particles liberated in this layer.

$$\frac{\mu_K}{\rho} = \frac{1}{E\rho}\frac{dE_K}{dl}\ (\text{cm}^2/\text{g}).$$

(15) The mass energy-absorption coefficient (μ_{en}/ρ) of a material for indirectly ionizing particles is $(1-G)\ \mu_K/\rho$, where G is the proportion of the energy of secondary charged particles that is lost to bremsstrahlung in the material.

Notes: (a) When the material is air, μ_{en}/ρ is proportional to the quotient of exposure by fluence. (b) μ_K/ρ and μ_{en}/ρ do not differ appreciably unless the kinetic energies of the secondary particles are comparable with or larger than their rest energy.

(16) The mass stopping power (S/ρ) of a material for charged particles is the quotient of dE_S, by the product of dl and ρ, where dE_S is the average energy lost by a charged particle of specified energy in traversing a path length dl, and ρ is the density of the medium.

$$\frac{S}{\rho} = \frac{1}{\rho}\frac{dE_S}{dl}\ (\text{MeV cm}^2/\text{g}).$$

Note: dE_S denotes energy lost due to ionization, electronic excitation, radiation, and atomic recoils. For some purposes it is desirable to consider stopping power with the exclusion of bremsstrahlung losses. In this case (S/ρ) must be multiplied by an appropriate factor that is less than unity.

(17) The linear energy transfer (LET) of charged particles in a medium is the quotient of dE_L by the product of ρ and dl, where dE_L is the average energy locally imparted to the medium of density ρ by a charged particle of specified energy in traversing a distance of dl.

$$LET = \frac{1}{\rho}\frac{dE_L}{dl} \text{ (MeV cm}^2\text{/g)}.$$

Notes: (a) The term "locally imparted" may refer either to a maximum distance from the track or to a maximum value of discrete energy loss by the particle beyond which losses are no longer considered as local. In either case the limits chosen should be specified. (b) The concept of linear energy transfer is different from that of stopping power. The former refers to energy imparted within a limited volume, the latter to loss of energy regardless of where this energy is absorbed.

Several other useful definitions are included below.

"Differential Energy Spectrum", $\phi(E)$ or $\Phi(E)$, means the distribution of energies of particles described respectively as a flux or fluence of particles having energies in a range E to E + dE, per unit energy interval, dE [particles/($cm^2 \cdot$ MeV)].

"Integral Energy Spectrum" means the distribution of energies of particles described as that flux or fluence having energies greater than some specified value [e.g., n/cm^2 (E > 3 MeV)].

"Fission Neutron Spectrum" is the energy spectrum of neutrons emerging from a fission reaction, usually in thermal neutron-induced fission of U-235.

Weapon and Laboratory Radiation Environment

The radiation environments produced by a nuclear detonation that concern us here are:

- Gamma rays, with energies up to a few MeV, primarily emitted as an intense short pulse, but with some contributions later from neutron interactions
- Neutrons with energies up to 14 MeV, also emitted as a short pulse, but spread in arrival time at a target by the dependence of their speed on energy.

The radiation environments produced by laboratory sources for TREE experiments (see Section 4) include:

- Bremsstrahlung X-ray spectra of peak energies 0.15 MeV to 10 MeV from flash X-ray machines

- Bremsstrahlung X-ray spectra of peak energies of 3 MeV up to 75 MeV from LINAC's (lower intensities than available from flash X-ray machines)

- Energetic electrons of energies of up to 75 MeV from LINAC's and up to 10 MeV from flash X-rays. (Ionization energy loss almost independent of energy above 1 MeV; penetration proportional to energy)

- Fission gamma rays and neutrons from nuclear reactors

- 14-MeV neutrons from accelerators (pulsed or steady state) using (d, t) reactions

- Gamma rays from isotope sources such as Co-60, useful only for low-dose-rate, steady-state irradiations.

Types of Radiation Effects and Simulation

Following are the types of radiation effects being considered and the relevant parameters describing the radiation environment which most strongly determine the effects; i.e., what type of average over the spectrum best characterize the response.

- Bulk ionization effects in semiconductors that depend primarily on the pulse width and the ionizing dose in the semiconductor from a short radiation pulse or on the dose rate in a pulse long compared to the relaxation time.

- Bulk ionization effects in insulators (conductivity) that depend not only on the dose rate and/or dose for radiation producing lightly ionizing primary or secondary tracks [electrons, photons (i.e., gammas or bremsstrahlung)] but also on LET for heavily ionized tracks (such as recoil protons from neutron collisions with hydrogen atoms).

- Charge-transfer effects (e.g., emission of electrons from surfaces) that depend on particle type and spectrum in a complicated, but calculable way. (For accurate work, specific theoretical or experimental calibrations of the energy dependence of charge transfer is required.)

- Displacement effects that depend primarily on the concentration of defects in the target crystal and secondarily on the clustering of the displaced atoms. They are produced mostly by neutrons.

The neutron-energy dependence of the displacement effectiveness in silicon is shown in Figure 5.1 and can be used to calculate the relative effectiveness of different spectra. Neutron damage also has a time dependence which is discussed in Section 6.1 under "Annealing".

In most cases, bremsstrahlung X-rays or electrons are used to simulate the short-pulse ionization effects produced by weapon gamma rays. In some cases, pulsed-reactor gamma rays are used to simulate the longer pulse ionization effects produced by the later arriving neutron-produced gamma rays. Generally, reactor neutrons are used to simulate displacement effects from weapon-spectrum neutrons. 14-MeV neutrons are used to a much lesser degree, primarily to check the expected energy dependence as shown in Figure 5.1.

The pulse-width requirements for simulation are determined by the characteristic relaxation time for the effect compared with the weapon produced pulse. Usually, these can be stated as a requirement for the radiation pulse to be either significantly shorter than, or significantly longer than, a characteristic relaxation time.

In the following discussions the dosimetry techniques can be separated into three classes:

- Neutron measurements, which are primarily applicable to displacement effects studies.
- Photon and electron measurements, which are primarily in support of ionization effects studies.
- Time dependence monitoring.

5.2 NEUTRON MEASUREMENTS

General Principles

In order to perform the weighting of different neutron energies by the factors shown in Figure 5.1, it is necessary to have a reasonably good picture of the neutron energy spectrum for energies above 10 keV. The contribution to displacement effects from neutrons below 10 keV in weapon or reactor environments is usually taken to be negligible. Many neutron-producing facilities will be able to provide fairly detailed spectral information of the free-field neutron environment to experimenters.

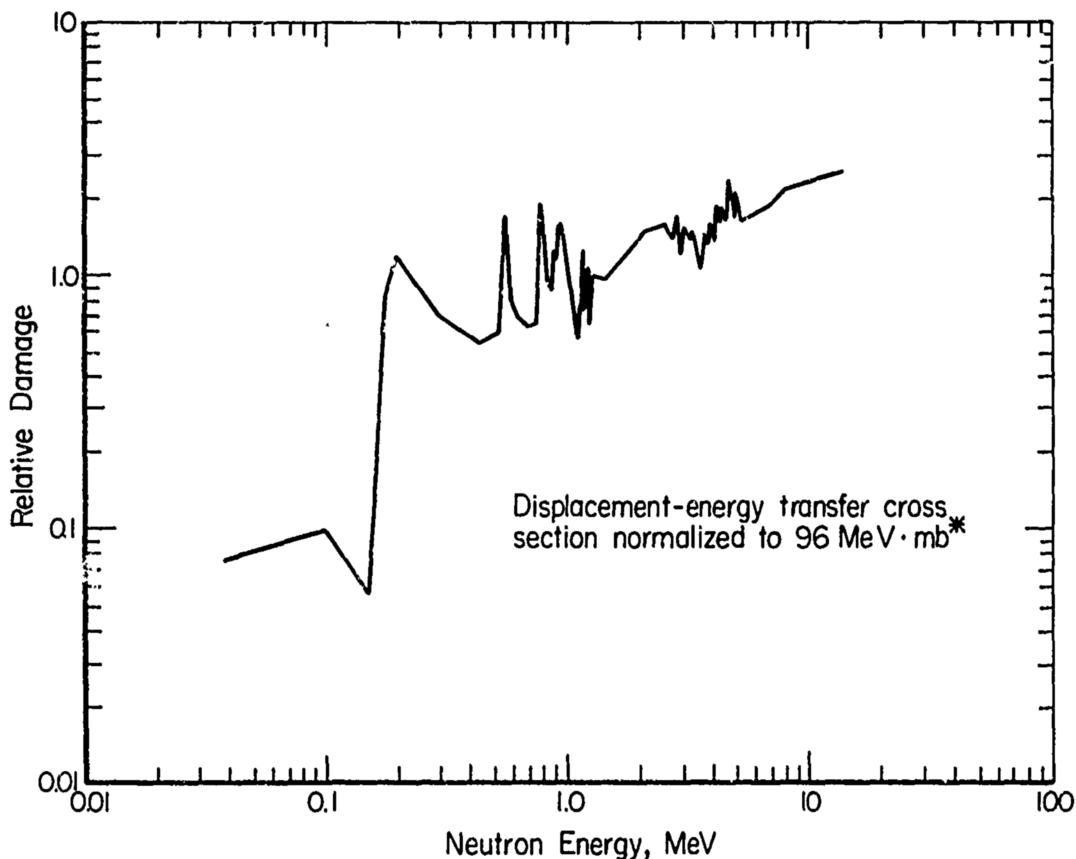

FIGURE 5.1. RELATIVE NEUTRON EFFECTIVENESS FOR DISPLACEMENT PRODUCTION

*Figure developed from data in "Weapons Effects Studies, Volume II, Radiation Effects on Interceptor Electronics", Ballistic Missile Defense Advanced Development Program, R. R. Holmes, J. P. Mitchell, D. K. Wilson, and W. H. von Aulock, Bell Telephone Laboratories (October 1, 1970). See also Table 5.5.

These spectra are in general determined from data obtained from high-resolution spectrometers (recoil proton, Li^6, He^3, etc), from low-resolution measurements utilizing activation techniques, or from reactor physics calculations. In general, if a radiation effects experiment is small, there is a good chance the free field spectrum will not be significantly perturbed and thus will be relevant to the experiment being conducted. If additional spectroscopy measurements are necessary, a decision must be made to determine the accuracies required. For high-resolution measurements, fairly expensive, time-consuming spectrometer measurement should be made. In most cases, however, lower resolution measurements will be acceptable and activation spectroscopy measurements will suffice. The operating power level of a reactor is usually used with known spectral information at usual test positions in a reactor to determine a first estimate of the neutron fluence in an experiment. Inasmuch as the techniques followed in a spectrometer measurement are highly dependent upon the instrumentation involved and the calculation of the approximate spectrum is beyond the scope of this manual, no recommended procedures will be given in this document. General recommendation will, however, be given concerning foil-activation techniques.

Foil-Activation Measurements

Foil activation techniques utilize neutron-induced reactions, for which there is a threshold energy or for which an artificial threshold can be produced by shielding. These neutron-induced reactions produce radioactive isotopes whose emitted radiation can be measured and used to determine the neutron fluence above the threshold. Schematically the process is illustrated in Figure 5.2. The top curve shows a typical neutron spectrum. The middle curve shows an idealistic response function for a threshold foil. The product of these two functions is shown in the bottom curve. The area under this curve is the total foil response (which is proportional to the foil's radioactivity). It can be seen roughly that the neutrons with energy above E_t contribute to the response, and the effective response coefficient (cross section) is almost a constant, σ_{eff}. Therefore, the foil response is approximately proportional to $\phi(E > E_t)\sigma_{eff}$.

A method based on irradiating a number of foils with different thresholds has proved to be very useful. The limitations to the foregoing approximate analysis are obvious: $\sigma(E)$ is not constant above E_t, and E_t itself is a function of the spectral shape. The steeper spectra tend to push E_t downward. In an actual situation, where the cross section is not constant but the spectral shape, $\Phi(E)$, is known, one can obtain a spectral averaged cross section from the expression,

$$\overline{\sigma} = \frac{\int_0^\infty \sigma(E)\, \Phi(E)\, dE}{\int_{E_t}^\infty \Phi(E)\, dE} . \qquad (5.4)$$

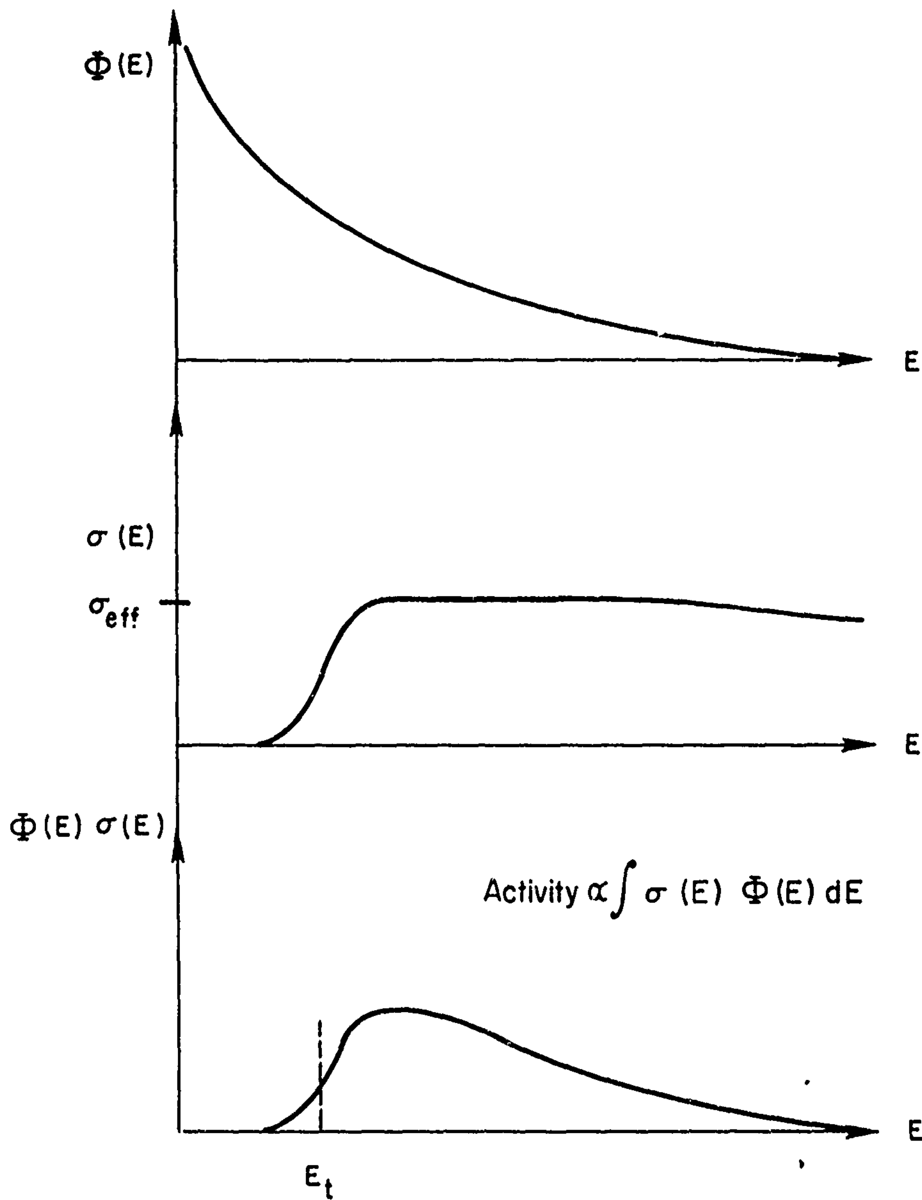

FIGURE 5.2. THRESHOLD FOIL METHOD

With this average cross section and the measured foil activity, the neutron fluence above the threshold energy, E_t, can be obtained. Since the spectrum is known, the total neutron fluence can thus be determined. This process is the most common measurement made in neutron effects testing. The most commonly used monitor foil material is S-32 which has a threshold energy of approximately 3 MeV. The Ni^{58} (n, p)Co^{58} reaction is also useful and is now seeing widespread use. If this method is used, one must be careful to insure that the experiment has not perturbed the spectrum, since large errors can unknowingly be introduced when utilizing this technique.

In situations where the spectral shape is not as well known, a series of threshold foils should be used. By assuming a spectral shape (e.g., a fission spectrum or "best estimate" for the particular reactor), an average cross section can be computed; and the fluence above the various thresholds, based upon the assumed cross section, determined. A curve of the integral fluence as a function of energy can be determined by this method. From this curve the ratio of total fluence to that above a monitor foil's threshold (e.g., S-32) can be determined so that further exposures can be made with the use of only the one monitor foil. Table 5.1 presents a list of commonly used foils, together with their effective thresholds and cross sections for a Watt fission spectrum. If the integral curve obtained in the previous manner differs considerably from an integral curve of the assumed spectrum, further data evaluation must be done, particularly in the range from 0.01 to 5.5 MeV.

Computer codes have been developed, such as SAND II, RDMM, and SPECTRA, which can be used to extract further spectral information from the set of activation data. The SAND II and SPECTRA codes compute both differential and integral spectra, based upon iterative techniques, and utilize both the response function differences of the various reactions over the entire sensitive energy regions and other physical information available about the source to obtain these solutions. However, the solutions thus obtained are always nonunique. RDMM computes differential flux as a continuous analytical function. If the spectral shape is calculated by one of these codes for the particular experimental setup, and if no changes in the setup are made, a single monitor foil may be used for subsequent irradiations. It is wise, however, to routinely check to insure that the spectrum has not changed unknowingly. Obviously, the accuracy of the neutron fluence measurements with foil activation techniques will be limited by the accuracy of the cross-section knowledge, the calibration of the counting equipment, and the degree of sophistication exercised in reducing the foil activities to fluence information.

The three codes may be obtained from the Atomic Energy Commission Radiation Shielding Information Center at Oak Ridge National Laboratory. Evaluated energy-dependent cross sections for neutron detector reactions are also available from the center, being tabulated on magnetic tape (SAND II cross-section library format).

TABLE 5.1 NEUTRON FLUENCE MEASUREMENT ACTIVATION FOILS*

	Threshold Energy	Effective Cross Section** (Watt Fission Spectrum)	Foil Thickness & Diameter (Inches)(Note 1)	Foil Weight (Grams)	Detectability (n/cm^2)(Note 2)	Half Life (Note 3)
ACTIVATION FOILS						
Cobalt	Thermal	37.2 b	.010 x .50	0.28	8×10^7	5.26 years
Gold	Thermal	98.8 b	.010 x .44	0.25	3×10^5	2.70 days
Rhodium	0.6 MeV	650 mb	.001 x .50	0.04	8×10^8	†57.5 min
Indium	1.5 MeV	365 mb	.020 x .50	0.60	3×10^9	†4.5 hours
Sulfur	3 MeV	300 mb	.38 x 1.5	18.0	2×10^8	14.3 days
Nickel	3 MeV	550 mb	.040 x .75	2.3	5×10^{10}	71.3 days
Titanium	5.5 MeV	230 mb	.016 x .50	0.25	3×10^{11}	83.9 days
Magnesium	6.3 MeV	67 mb	.065 x .75	0.78	2×10^9	†14.96 hours
Aluminum	7.5 MeV	79 mb	.060 x .75	1.2	8×10^8	†14.96 hours
Iodine	11 MeV	980 mb	.25 x .75	4.3	1×10^9	12.8 days
Zirconium	14 MeV	1.6 b	.060 x .75	2.8	5×10^8	3.27 days
FISSION FOILS (Note 1 & 4)						
Plutonium-239	10 keV	1.7 b	.075 x .94	1.0	1×10^{10}	Fission Product
Neptunium-237	0.6 MeV	1.65 b	.075 x .94	0.10	4×10^{10}	Fission Product
Uranium-238	1.5 MeV	550 mb	.075 x .94	5.0	5×10^9	Fission Product
ACTIVATION FOILS (FUSION NEUTRONS)						
Copper(a)	14.4 MeV	530 mb				9.9 min
Fluorine(b)	14.1 MeV	61.3 mb				109.7 min

Notes: 1. Cadmium covers are normally used with all activation foils except sulfur and bare gold. Fission foils have cadmium covers inside ellipsoidal B-10 balls having 1.9" minor diam x 2.1" major diam".

2. Detectability data for fission foils applies only if foils are counted 1 hour after exposure or within one half-life for other foils. The data are presented for relative comparison only. Actual values may vary for different counting systems.

3. Dagger indicates that on-site counting and preliminary data reduction may be required because of short half-life.

4. Use of fission foils requires prior AEC approval.

* Data taken from EG&G, Inc. data sheet (December, 1970); values confirmed in private communication with K. C. Humphreys, EG&G, Inc., Santa Barbara Division (March, 1971).

** Cross sections given are for the isotope whose activation is measured and not for the naturally occurring element.

(a) Proceedings of the 1965 International Conference on Modern Trends in Activation Analysis, College Station, Texas (April, 1965).

(b) "Tentative Method for Expressing Radiation Hardness", J. M. McKenzie, Sandia Laboratories, SC-DR-710045, (March, 1971).

Methods for interpreting measured neutron spectra and reporting in terms of equivalent fluence units are given in Section 5.7. A different approach, which does not measure spectrum, but rather obtains an integrated effect of the neutrons, is discussed in the next few paragraphs (RDM).

Radiation Damage Monitor (RDM)

A radiation damage monitor is a semiconductor device, typically a transistor, that is useful in determining the relative damage effect of neutron environments on semiconductor devices. The RDM is based on the premise that, within a group of devices of which a statistically significant fraction have been tested and proven to have a similar, predictable response to neutron radiation, the remaining portion of that group will respond to neutron environment in a manner similar to that described by the initial test sample.

For example, the change in reciprocal gain of some transistors due to damage in the bulk portion of the device can be given by

$$\Delta \frac{1}{h_{FE}} = t K \phi$$

where

t = base transit time, s

K = empirical radiation damage factor, $cm^2/(n \cdot s)$

ϕ = neutron fluence, n/cm^2 (E>10 keV, fission spectrum)*.

Neutron fluence, therefore, is linearly related to the change in the reciprocal gain of a transistor. Transistor RDM's typically have a linear range of about 1.8 decades. By using several different device types, the range from 10^{11} to 10^{15} n/cm^2 can be covered.

In using these devices, the n/γ ratio should be greater than 10^8 n/[$cm^2 \cdot$ rads(Si)] so that surface effects due to ionizing radiation may be neglected. All identical devices should be irradiated at the same temperature and measured at the same temperature. A uniform rather than a varying temperature is preferred, and care should be taken to store RDM's at room temperature between irradiation exposure and measurement.

To take into account the effects of annealing, all measurements should be made at some standard time after irradiation (24 hours). The Δh_{FE}^{-1} should be in the range of 0.01 to 0.30.

*See Section 5.7.

RDM's have been used as absolute monitors of neutron fluence by determining their response to the neutron fluence at a particular location in a particular reactor and using this as a reference neutron environment. However, the use of RDM's as an absolute fluence monitor is not recommended. The greatest value of RDM's is as a relative measurement device for comparing neutron environments in different experiments or at different locations within an experiment.

For more information on the selection and use of RDM's see "Handbook for Predicting Semiconductor Device Performance in Neutron Radiation", AFWL-TR-67-54 (ReV), by Frank and Taulbee (April, 1968) or "Exploratory Development of a Radiation Damage Exposure Measurement Technique", AFWL-TR-67-63, by Pobling and Taulbee (October, 1967).

5.3 PHOTON AND ELECTRON MEASUREMENTS

General Principles

For TREE applications, photon and electron measurements are primarily in support of ionization effects experiments. Therefore, as discussed in Section 5.1 under "Types of Radiation Effects and Simulation", the dose (or ionization density) in the material of interest is most closely related to the effect. For high-energy electrons and for the Compton effect of high-energy photons and low- or medium-Z material an approximate rule of thumb (± 5 percent) is that the dose is proportional to Z/A of the target material, where A is the mass number. For higher accuracies even a crude spectral shape used with Equations 5.1 and 5.. can convert dose measured in any dosimeter, D, to the dose in the material of interest, R, viz.,

$$R = D \frac{\int R(E)\, \phi(E)\, dE}{\int D(E)\, \phi(E)\, dE} . \quad (5.5)$$

For electron beam exposures in a known spectrum, dose may be converted from one material to another by using Equation 5.5 and dE/dX values given in the literature*.

*"Tables of Energy Losses and Ranges of Positrons and Electrons", NASA Tech Rpt. SP-3012, M. J. Berger and S. M. Seltzer (1964).

The use of high-energy electrons, $0.5 \leq E \leq 15$ MeV, to produce ionization effects is straightforward. Their rate of energy deposition is almost independent of energy and material, $Z < 40$. The only cautions are that the electron energy needs to be high enough to penetrate the target and radiative losses must be considered. In addition, thin plates can scatter a small-diameter electron beam into a cone-shaped beam. Therefore, objects in the beam ahead of the target, such as a chassis, must be in place during dosimetry calibration.

The maximum range (depth of penetration) is approximately

$$R_e = 0.412\, E^{(1.265 - 0.0954 \log_e E)} \text{ for } 0.01 \text{ MeV} \leq E \leq 3 \text{ MeV}$$

$$R_e = .530\, E - .106 \text{ for } 2.5 \text{ MeV} \leq E \leq 20 \text{ MeV}$$

where

$$R_e = \rho \ell \text{ in gm/cm}^2\text{, and E is in MeV,}$$

where ρ is the material density in g/cm^3, and ℓ is thickness in cm.

Photons deposit energy in material primarily through secondary electrons created in photon interactions with matter. Therefore, most of the above discussion on electrons is pertinent to dose deposition by photons.

The response function relating dose deposition to the photon energy is known as the mass absorption coefficient. Shown in Figure 5.3 are mass absorption coefficients for silicon, used as an example of a typical low-Z material. As can be seen for these materials, the absorption coefficients are essentially independent of energy over the energy range $150 \text{ keV} \leq E \leq 1$ MeV. Based upon these characteristics, the absorbed dose per unit energy fluence for bremsstrahlung distributions over this energy range is fairly insensitive to the spectral shape, and dose measured in a low-Z dosimeter can be converted quite easily to dose in a low-to-medium-Z material of interest.

Since photons (gamma or X-rays) are indirectly ionizing particles and lose energy through the creation of high-energy electrons which subsequently lose energy through further ionization, extra care must be taken in accounting for lack of electron equilibrium. If a pure photon beam were incident on a slab of material, the energy deposition as a function of depth in the slab would be as shown schematically in Figure 5.4. Although the amount of energy initially imparted to the material by photons decreases with depth, the actual dose builds up to a maximum at a depth corresponding to the maximum electron range, then decreases very slowly at the rate of attenuation of the photon beam. This loss of

dose to the material near the surface results from the beam not having reached secondary electron equilibrium. At a point corresponding to the maximum electron range and beyond, the beam is in electron equilibrium, meaning that for every secondary electron leaving a small region of interest, another enters the region or, equivalently, the ratio of electrons to photons remains constant. For high photon energies (>200 keV) in low and medium atomic number materials ($Z < 40$), the ratio of electrons to photons is almost independent of material. At lower energy and higher Z the ratio changes when the beam goes from one material to another in a similar fashion to that shown in Figure 5.4. Therefore, in order to avoid complications from nonuniformity of dose and to provide accurate dosimetry, exposures should be performed under conditions of electron equilibrium. Unless electron equilibrium is established correctly in the radiation source, a foil of approximately the correct Z and an electron range thickness should be interposed in front of the target. The same rule applies to the cases of dosimeters.

When reporting absorbed dose measurements, the rad – the unit of absorbed dose of radiation – is used. One rad corresponds to the deposition of 100 ergs/gm of radiation energy in a small volume of the material of interest at a point of interest. It is important to note that the material in which the energy is deposited must be specified when reporting with this unit of measure; i.e., rads (Si), rads (H_2O), etc. Dosimeters for use in TREE experiments should be calibrated in known spectra to read rads (dosimetry material). Small dosimeters typically read rads (wall material), although for a given spectrum they may be calibrated to read out in other kinds of rads. This is true of active (say PIN) as well as passive dosimeters, when the dosimeter is too small to establish its own charged-particle-equilibrium in the photon flux.

If nonconducting dosimetry materials or experiments are exposed to intense electron beams characteristic of flash X-ray machines, care must be taken to account for the effect of the potential buildup in the sample (from trapped electrons) on the dose to the sample.

We now turn to a description of various dosimeters useful for ionization effects studies with photons and electrons.

Radio-Photoluminescent Devices (RPL)

In RPL devices, irradiation produces stable flourescence centers that may be stimulated by subsequent ultraviolet (UV) illumination to emit visible light. The total light emission is a measure of the absorbed dose in the RPL material (if in electron equilibrium) which was previously exposed.

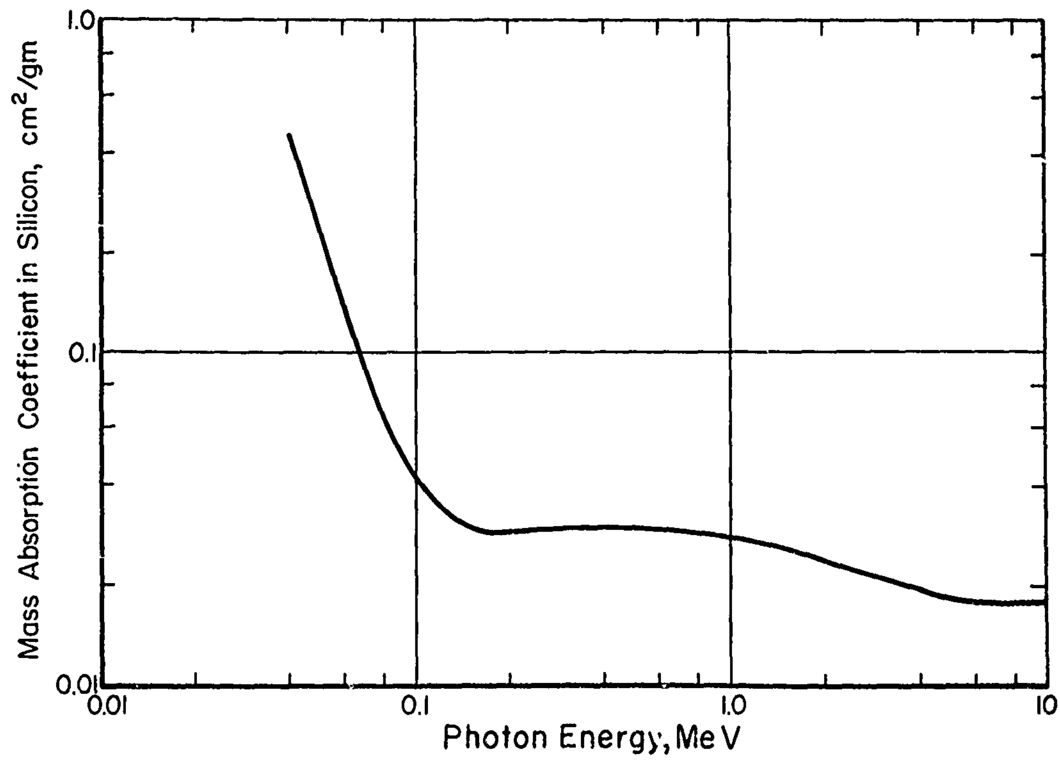

FIGURE 5.3. MASS ABSORPTION COEFFICIENTS FOR GAMMA RAYS IN SILICON

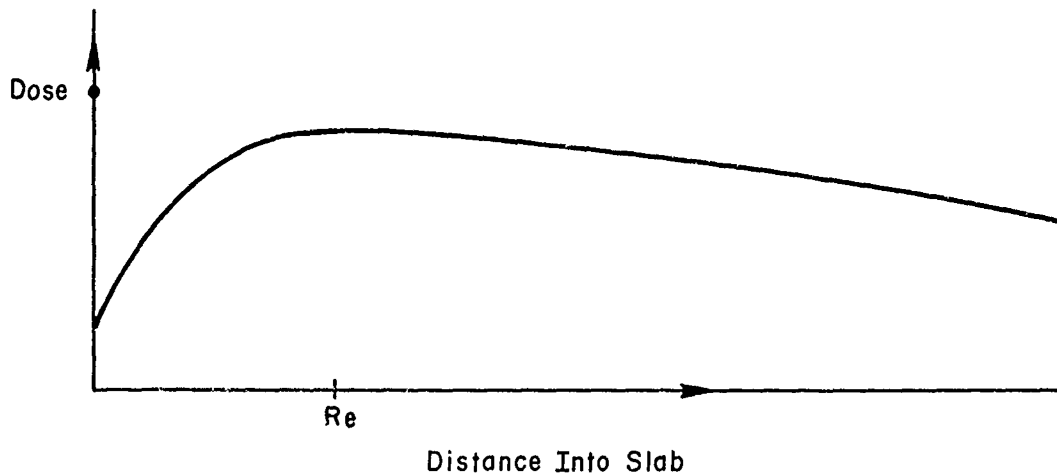

FIGURE 5.4. ENERGY DEPOSITION BY PHOTONS

An example of a RPI dosimeter is a silver metaphosphate glass rod or plate system. These dosimeters can also be used with special energy shields that sufficiently suppress the low-energy response of the high-Z silver by absorption so that the total response is essentially independent of energy, yielding a reading proportional only to exposure (photon fluence) for photon spectra of energy $100 \text{ keV} < E < 5 \text{ MeV}$. By knowing the total fluence and the spectral shape, one can evaluate Equation 5.1 to determine the dose to any other material. With a thinner shield matching the average Z of the glass, it would measure dose in the glass.

Glass rods should be cleaned and read before irradiation for expected dose < 100 rads (glass). They should not be routinely reused. If absolutely necessary, annealing is possible using procedures documented in the literature. Extreme care should be taken to avoid glass-rod chipping.

There is evidence to indicate that some fading of the glass rods occurs, especially when the rods are subjected to prolonged exposure to ultraviolet light. The readings appear to reach a maximum value at about 24 hours after exposure and then decrease with time. The readings are down about 30 percent from the 24-hour reading in 6 weeks, and thereafter the rate of fading decreases with time. Until this fading with time can be investigated further, the safest approach seems to be frequent recalibration with a set of very old (several years at least) rods. For accuracy in reading, the system should be calibrated and used by reading rods 24 to 48 hours after exposure.

For high-energy electron-beam dosimetry, the rods should be used directly on or in the experiment without shields; then, one is measuring the local absorbed dose in rads (glass).

Optical Density Devices

In optical density devices, radiation produces stable color centers that absorb light. Measurements of the optical transmission, usually at a fixed wavelength, can be related to the dose in the active material.

An example of an optical-transmissivity-change dosimeter is a cobalt-glass-chip system. At doses greater than 10^6 rads saturation is approached and the readings can become very inaccurate. Both an energy-compensation shield and a thermal neutron shield are required when using cobalt-glass chips in a nuclear reactor environment. A bismuth-lead-borate glass also has been developed as a high-level gamma dosimeter specifically for use in mixed gamma-neutron environments.

Other materials used as colorimetric dosimeters include dyed plastics such as blue cellophane, cinemoid films, etc. Again, these should be used within their accurate range ($\sim 10^6$ rads) and corrections may be required at very high dose rates. Before using a particular dosimetry system one should consult the literature to determine the rate and environment effects which may be characteristic of the particular system.

TABLE 5.2. CHARACTERISTICS OF SOME RPL AND OPTICAL DENSITY DEVICES*

Dosimeter	Range, rads	Accuracy, percent	Rate Dependence, rads/s	Fast-Neutron Response, rads/n-cm^2
High Z, silver phosphate rods	10^1 to 2×10^4	± 10	None to 10^9	$<3 \times 10^{-10}$
Low Z, silver phosphate rods	10^1 to 2×10^4	~± 10	None to 10^9	$\sim 6 \times 10^{-9}$
Cobalt glass	10^4 to 4×10^6	± 10	None to 10^9	$<3 \times 10^{-10}$
Bismuth glass	10^6 to 10^{10}	± 10		Negative

* Fast Burst Reactors, Technical Coordinators, R. L. Long & P. D. O'Brien, USAEC Publication CONF-69-0102, 1969, "A Review of Some Passive Dosimetry Methods Used in Radiation-Effects Studies With Fast Burst Reactors" (K. C. Humpheries) p 508.

Thermoluminescent Devices (TLD)

TLD irradiation produces metastable centers which can be induced to emit light by heating. The amount of light is related to the dose in the TLD material.

An example of a TLD dosimetry system uses lithium fluoride with a readout unit that heats the exposed material and registers the area under the luminescent peak. The heating rate should be checked for linearity or at least reproducibility, and for doses below 1 rad(LiF) the readout should be performed with the material in an inert or dry nitrogen atmosphere. The TLD materials can be annealed but should never be used at low doses without recalibration. The sensitivity of TLD materials can change with repeated annealings, therefore periodic checks of the sensitivity are in order.

No TLD material should be used as delivered by the vendor. Each production batch should be individually characterized by the user before use in his particular radiation environment. Never rely upon vendor specs for any accurate TLD measurements. Phosphor sensitivities, linearity of phosphor response to absorbed dose, TL fading characteristics, etc. are strongly dependent on processing methods and/or impurity conditions within the TLD materials. These variables are not yet sufficiently controlled by vendors to justify a carte blanche attitude on the part of the user.

The TLD reader should be checked regularly for proper operation of the phototubes and heating units. A regular (daily or weekly) calibration should be made with a Co-60 or other standard source, and a log kept to show trends. TLD system manufacturers' recommendations for care of the reader should be followed. To check heating rates, and to allow for examination of the entire glow curve, the readout units should be provided with outputs for strip-chart recording of temperature and light output.

The wall material surrounding the TLD material should match the TLD atomic number and should be thick enough to establish electron equilibrium. Then (if the calibration is correct) the dose measured will be that of the TLD material; otherwise the dose will be intermediate between that for the TLD material and that for the wall material.

TLD materials can be obtained in several forms and chemical compositions. Examples include powders, forms that are extruded, encapsulations in Teflon, etc. Chemically differing dosimeters such as calcium fluoride also are available.

Manganese-activated calcium fluoride is, for some applications, a more useful TLD material than LiF for TREE work since: (1) it does not saturate at as low a dose; that is, it is not as easily damaged; and (2) its Z is closer to silicon, so that with an aluminum or silicon case one can get a good approximation of the absorbed dose in silicon. Below approximately 200 keV, energy-correction shields are necessary for the CaF:Mn dosimeters but not for the LiF dosimeters. (See Section 5.5 Spectral Filtering.)

Thin Calorimeters

A thin calorimeter determines the dose by measuring the temperature rise in a small sample of known material. Since the temperature rise can be converted to energy deposition (dose) by the material's specific heat, the measurement is a direct determination of the average dose in the sample. If the sample is thin – i.e., it absorbs a negligible fraction of the incident radiation and the incident beam is in electron equilibrium for the calorimeter material – the temperature rise is independent of thickness.

The three important elements of a thin calorimeter are the absorber, the temperature sensor, and the thermal isolation. The absorber can be any material, preferably having approximately the correct atomic number as judged by the effect being studied, and also preferably being a good thermal conductor to assure rapid thermal equilibrium. Metal foils (Be, Al, Fe, Cu, Ag, Pt, Au) have been used successfully as well as thin semiconductor chips (Si, Ge).

The temperature sensor should represent a small perturbation on the absorber. A thermocouple satisfies this criterion well, particularly if it almost matches the atomic number of the absorber. A small copper-constantan thermocouple on a copper foil is a good example. A more sensitive calorimeter results from using a small thermistor as both absorber and temperature sensor. A chemical analysis of the thermistor can establish its effective atomic number, and a calibration against a known material is required to establish the combination of specific heat and temperature coefficient. Care must be taken in assembly to minimize the amount of solder used in attaching leads, because this may enhance the amount of higher Z material. Resistance welding can be used to eliminate this problem. If the thermistor is not thin to the radiation, the temperature measurement must be performed for a long enough time to insure that thermal equilibrium is established within the thermistor (0.1 to 1 s).

In order to measure accurately a small, sudden temperature rise, some degree of thermal isolation is required. Obviously the leads to the temperature sensor should be small wire (~3 mils). For single pulse measurements, a block of styrofoam provides good isolation, but the heat lost to the inside layer of styrofoam requires a small correction, particularly for very thin calorimeters. Use of the calorimeter in vacuum also provides excellent isolation. For accurate measurements, especially on a short string of LINAC pulses, the absorber can be suspended in a small evacuated can with water-cooled constant-temperature walls and a thin window for beam entrance. The detailed design depends on the radiation beam being measured and the accuracy requirements. The design may have to take into account scattering from the walls of the chamber.

For single pulses typical of flash X-ray machines, a cooling curve should be established and exponentially extrapolated to zero time to determine the temperature at the time of the burst.

The response of the calorimeter is calibrated by the specific heat of the absorber and the temperature calibration of the sensor. In electron-beam measurements, if the calorimeter material is the same as the experimental material being tested, the absorbed dose in the experimental material can be measured directly. If, however, the dose to the calorimeter must be converted to dose in another material of significantly different atomic number, corrections must be made for differences in dE/dX, backscattering, and bremsstrahlung losses.

PIN Detectors

A reverse-biased PIN diode (usually Si, although a cooled Ge device can be used) collects charges produced by ionization in the intrinsic

semiconductor region. Its calibration is based on the known efficiency for producing electron-hole pairs (3.7 eV/pair in Si) and the active volume of the junction region. The charge collection time is short (on the order of nanoseconds) and therefore a PIN diode can be used to measure not only the dose in the semiconductor but also the shape of the radiation pulse [dose rate (Si) versus time]. Care must be taken to use the detector only at low enough dose rates where the linearity is established. At high dose rates [$\sim 10^9$ rads (Si)/s] the internal electric field is modified by the high currents and the output becomes nonlinear. For this and other reasons a PIN detector is normally limited to dose rates of less than 10^{10} rads (Si)/s. It is important to note that a PIN detector will not correctly measure the dose unless electron equilibrium in the silicon active volume has been established. Many standard commercial detectors can derive measurable portions of their signal from the high Z case or from their tantalum plate contacts. One can, however, obtain from manufacturers, on special order, degenerate silicon contacts to which the leads are attached, or detectors with very thin contacts so that they may be placed in electron equilibrium through the introduction of additional silicon (or aluminum foils). One should be careful to determine if the addition of inactive material to create electron equilibrium for the most energetic portion of a distributed spectrum has attenuated the low-energy portion of the spectrum, and a suitable correction should be made to determine the dose to a thin silicon sample.

PIN diodes like other semiconductor devices are subject to degradation due to displacement damage. The results of the damage are a decrease in the intrinsic silicon lifetime and resistivity resulting in an increase in leakage current. Neutron fluences of $>10^{12}$ n/cm^2 (E > 10 keV, fission) are sufficient to change the calibration of a silicon PIN diode. PIN devices may also be damaged by high energy gamma dose-induced displacement damage at above, say, 10^4 to 10^5 total rads of such dose. In general, as long as the minority carrier lifetime is much longer (10x) than the collection time, the device will operate satisfactorily.

PIN diodes can also be damaged by high current for long pulses of electrons or photons, or by repetitive pulses. Because of the possibility of damage they should be calibrated routinely and checked by a well calibrated passive system.

Compton Diode and SEMIRAD

Compton diodes and SEMIRADS are based on the charge transfer of electrons between materials under irradiation. The calibration depends on the spectrum and is not uniquely related to dose in any material, except for a limited range of spectra. The time resolution is potentially excellent and such devices are very useful as pulse-shape monitors at high dose rates. For very high dose rates, Compton diodes are recommended since SEMIRADS will undergo space charge saturation.

Scintillator-Photodiode Detectors

Various organic scintillators having both fast response and a large linear range are available for measurements of ionizing dose rate versus time. Examples are plastics such as Pilot B and NE102 and organic liquids such as NE211, and NE226, which have 2- to 3-ns resolution. At high dose rates the light emitted is intense, so that the photodiode needs to be designed so as to avoid space charge limitation. An FW114 is frequently used with adequate bias voltage to avoid saturation. This combination measures energy deposition in the scintillator, i.e., rads (scintillator). Organic scintillators have been shown to have nonlinear characteristics at high rates (~10^{11} rads/s) and should not be used at rates above this value.

Faraday Cup

A Faraday cup can be used for electron-fluence measurements. The measurements are convertible to rads (Z) entrance-dose units in a material to be inserted in the beam if the incident electron energy is known. Values of electron energy loss rate, dE/dx, are given in NBS Circular 577, "Energy Loss of Electrons and Positrons". When using a Faraday cup to monitor an electron beam, a guard voltage should be applied and a reentrant cup used with a low-Z stopping material, backed up with a higher Z shield material. The incident beam must be collimated and accompanying secondary electrons must be swept out by a magnetic analyzer. For accurate work, the whole cup should be placed in a vacuum; for fast pulsed electron-beam work, if the pulse shape is to be determined, a coaxial cup design matched to the cable impedance may be desirable.

The accuracy achievable with the proper Faraday cup technique is good enough to warrant use of Faraday cups as calibration tools. The much greater convenience of a simple, but less accurate, low-Z stopping block current collector also makes this a useful tool in LINAC dosimetry.

Summary of Typical Dosimeter Sensitivity

Tables 5.3 and 5.4 list typical gamma-ray and neutron sensitivities (much of it experimental, but some vendor's data) for a variety of dosimeters used in TREE work. Some of these sensitivities may be varied by geometrical design, voltages applied, and other methods, so the data are to be taken as representative only. For actual experimental work, the particular dosimeter and readout system should be calibrated to determine actual values. It should be noted that the thermal neutron response of the dosimeters must be considered because they are not necessarily negligible.

TABLE 5.3. GAMMA-RAY AND NEUTRON SENSITIVITY OF ACTIVE DOSIMETERS

Dosimeter Type	Model	Gamma-Ray Sensitivity, coul / rad (air)	Neutron Sensitivity, coul / n/cm²(E)
Silicon PIN	004-PIN-2501E	7×10^{-9}	5×10^{-17} (14 MeV) 2×10^{-18} (fission)
Photodiode-scintillator (FW114)	Pilot B NE 211 (xylene) NE 226 (C_6F_6)	2×10^{-8} 1×10^{-9} $\sim 1 \times 10^{-9}$	1×10^{-18} (fission) 1.5×10^{-19} (fission) 1×10^{-21} (fission)
SEMIRAD, Ti wall	Econ 7318	1.4×10^{-11}	3.5×10^{-20} (14 MeV) 1.5×10^{-21} (fission)
Stainless steel	Reuter Stokes, gamma sensitive	$1.9\text{-}7 \times 10^{-11}$	Negligible (fission) Not negligible (fusion)
Stainless steel, U-238	Reuter Stokes, neutron sensitive	4.0×10^{-11}	3×10^{-22} (fission) 1×10^{-21} (14 MeV)
Compton diode	Representative model, EG&G	1.6×10^{-11}	5.3×10^{-21}
Cerenkov detector	Representative model, EG&G	2.9×10^{-10}	8×10^{-19}

TABLE 5.4. NEUTRON SENSITIVITY OF PASSIVE GAMMA-RAY DOSIMETERS

Dosimeter Type	Material	Neutron Absorbed Dose, 10^{-10} rads (air)/(n·cm^{-2})						
			Neutron energy, MeV[a]					
		Thermal	1	2	3	5.3	8	14.5
TLD	CaF_2: Mn							
	Vacuum tube type	1.23	0.59	0.71	0.57	5.4	0.12	1.8
	Micro TLD	.88	1.7	1.8	--	7.2	5.9	3.9
	LiF							
	TLD-100	175	2.0	4.6	5.6	12.3	13.1	20.2
	TLD-600	548	7.8	9.6	9.6	19.3	15.8	42.1
	TLD-700	None	3.7	7.1	7.3	17.5	14.0	32.4
RPLD	$AgPO_4$ glass							
	High Z	3.2	≤1.4	1.3	--	≤1.5	2.5	5.6
	Low Z	25	≤2.0	≤3.0	--	≤7.2	2.2	4.5
UV trans-mission	Cobalt glass	31.8	51 ± 50% for fast neutrons					

Note This table was developed from private communications to D. J. Hamman of Battelle Memorial Institute from Nancy Gibson of the U.S. Army Nuclear Defense Laboratory.

(a) Underlined values were obtained with dosimeters irradiated in an energy discrimination shield. All others were bare.

Spectrum Monitoring

In nuclear physics studies, elaborate tools have been developed for detailed photon spectrum measurements. For TREE facilities, however, the spectral information accuracy requirements rarely justify such methods. Simpler techniques based on a knowledge of the general source characteristics and some absorption measurements, along with any spectral information provided by the facility operations group, are usually adequate.

A combination of dosimeters having different atomic numbers and shielding is recommended for spectral monitoring of the TREE environments; for example, high- and low-Z bare glass rods, or LiF and $CaF_2(Mn)$ in plastic and aluminum container pairs, respectively, to read rads (low Z) and rads (high Z). The dose ratio is a measure only of the spectral quality, not of the spectral details; if the ratio is appreciably different from 1.0, the spectrum may contain either low-energy components (< 200 keV – a very soft spectrum) or very high energy components (> 5 MeV). This point should be checked, if there is some doubt considering the source, by measuring the broad-beam absorption curve or first and second half-value layers in Al or Cu and comparing it with that for Co-60 (first HVL = 17 g/cm^2 Al or 9 g/cm^2 Cu).

If too soft a spectrum is indicated, experimental design should be changed, since environment correlation may be difficult: the radiation may be attenuated severely by transistor cans, and this poses the problem of determining the actual dose in the device from an exposure or dose measurement outside the can. A ratio of dose in material (Z = 29) to dose in material (Z = 13) higher than 1.5 indicated an appreciable amount of radiation below 200 keV. Extreme care should be taken in experimental design with such low energies to assure that the dosimetry measures the doses desired at interior points of the experiment.

Normally detailed spectral information is not needed for routine TREE work since (1) the entity of interest in gamma-ray effect simulation is the microscopic and macroscopic dose deposition pattern – the depth-dose distribution and sometimes the LET, (2) the absorption coefficients for semiconductors and most insulator materials do not vary much for photon energies in the range 200 keV to 10 MeV, and (3) most useful TREE sources have energies within this range. However, gamma-ray simulation facilities should have enough spectral information to be able to convert dose measurements in the dosimetry materials used to absorbed dose in all materials; that is, to approximately evaluate the equations given in Section 5.1.

5.4 PULSE SHAPE MONITORING

In many experiments it is desirable to monitor the radiation pulse shape with a sensor that monitors a quantity proportional to the radiation intensity, but that must be calibrated in terms of the required dosimetry quantity at the sample position. The primary requirements for such a monitor are adequate time resolution, linearity, and proportionability to an appropriate dosimetry quantity. This last requirement can be met most easily if the radiation spectrum is independent of time during the pulse.

Examples of such monitoring measurements are:

- Tube current measured in flash X-rays (not recommended because the beam energy is time dependent)
- Current of LINAC electron beam measured with current transformer or secondary emission foil (excellent if beam is energy analyzed and collimated)
- Peripheral radiation intensity measured with PIN, Compton diode, scintillator, or SEMIRAD (use with caution because measurement may be sensitive to time-dependent spectrum in flash X-ray, and calibration may be affected by scattering from the target)
- Reactor power pulse monitored with a neutron-sensitive ion chamber (excellent for neutrons, but not good for gammas because of delayed gamma tail)
- Reactor gamma pulse monitoring with a neutron-insensitive ion chamber.

5.5 RECOMMENDED ENVIRONMENT MEASUREMENTS AND PROCEDURES

It is recommended that experimentalists provide for routine monitoring of remote facility dosimetry and environmental measurements whenever possible. This is to insure that the experimental data do not become worthless because of failure or loss of the dosimetry services provided by the remote facility. The monitoring should include at least some of the following procedures:

- Expose passive dosimeters (or foils) from the remote facility in one's local isotope (Co-60), or other source, along with locally calibrated and read dosimeters (or foils). The remote facility should then read out its own dosimeters (or foils), and a comparison should be made between the experimentalist's local dose (or fluence) determination and that of the remote facility. This process should be extended to cover different types of dosimeters to avoid systematic errors. The principle of this recommendation applies to both gamma-ray doses and neutron exposures.
- Place one's own passive dosimeters in and on the critical experiments as a check on the remote facility service. One's own dosimeters are then read out later when convenient, presuming that the facility dosimetry results are immediately available. When reading one's own dosimeters later, be sure to make any necessary corrections for fading.

- Use a calibrated active dosimeter which can be read out along with other signals. This step may be necessary if (as is too often the case) the remote facility does not provide immediate dosimetry results.

- Make an estimate of the perturbation of the free field spectrum (curves of which should be provided by the facility staff) caused by the presence of the experiment, and the effect of this perturbation on the results of the experimental correlation.

Remember, it is the responsibility of the experimentalist, not the facility operations staff, to determine the adequacy of the radiation measurements made in support of his experiment. The experimentalist should hire an outside dosimetry service if he does not have such services available in-house.

Flash X-Ray Dosimetry

When irradiating circuits or subsystems at flash X-ray facilities, it is recommended that every necessary dose point be monitored by passive dosimetry on every shot. This is because of the shot-to-shot variations in exposure and in beam position.

It is recommended that high-Z and low-Z dosimetry pairs be exposed at least occasionally to check beam quality; also, dosimeters should be used on front, sides, and back of large experiments to check on exposure uniformity and on beam structure and location. If dose to a component or material not in electron equilibrium is needed, the exact configuration should be mocked up with dosimetry material in place of the component, and measurements should be made to determine the effect of the nonequilibrium.

Active dosimetry, for pulse shape and machine diagnostics, should include at least one of the following three diodes:

- A calibrated scintillator photodiode. A fast scintillant should be used, and a high enough voltage applied to the diode so that at expected dose rates all current is collected to avoid space-charge limitations. If this cannot be done by any other means, the active dosimeter should be moved back from the target to reduce the expected dose rate.

- A calibrated PIN diode. A high enough voltage should be applied to assure that the PIN diode response is linear, and the load circuit should be arranged so that the detector voltage is not reduced during the pulse to too low a value. Otherwise the detector should be moved to a lower dose rate position. A possible high-dose

circuit involves shorting the output through a current transformer; another involves a low value of load resistance.

- A calibrated SEMIRAD or Compton diode. If one must operate actively in the high-exposure rate part of the beam, a gamma-ray SEMIRAD with adequate applied voltage to preclude space-charge limitations or Compton diode may be used.

Active measurements at any TREE facility must be well shielded against RF noise. Cable effects on signal shapes also must be reckoned with and ground loops must be eliminated (see Section 2.5). Electron-beam dosimetry should be done with a calorimeter if possible. Extreme care must be exercised to assure that samples, dosimeters, etc., are properly grounded so that the potential buildup in the sample does not affect the manner in which energy is deposited.

LINAC

For bremsstrahlung work, the precautions and dosimetry measurements at a LINAC facility are similar to those at a high-energy flash X-ray facility, except that the pulse-to-pulse variability may be much less, and the spectrum is constant during the pulse if the beam is magnetically analyzed. The collimated electron beam should be monitored on each pulse, preferably with a secondary emission detector or current transformer. This monitor can be calibrated against dose at the sample position using passive dosimeters or a thin calorimeter. Monitoring the beam with a PIN or scintillator detector is not recommended because the direct beam is frequently not available and the peripheral beam is affected by scattering from the target.

For electron-beam work, dosimeters such as RPLD glass rods, cobalt glass chips, LiF, or CaF_2, may be calibrated and used without shields to measure the absorbed dose in rads (dosimeter).

If the LINAC beam is not magnetically analyzed and collimated, its energy may change during the pulse, and the bremsstrahlung exposure pulse shape will not be the same as the beam current pulse shape. Also, the pulse observed behind the attenuating or scattering material may be different from the beam current pulse.

Nuclear Reactors

The neutron flux and spectrum at a reactor facility (either bare critical assembly or thermal reactor) depends on the rate of fission in the reactor and the absorbing/scattering geometry. Therefore, the exposure

geometry, including absorbers, scatterers, fuel element locations, etc., should be carefully controlled and calibrated. It is recommended that for each exposure geometry (with experiment in place) a set of threshold foils be exposed to determine the spectrum shape. Then, for each irradiation, a single foil type (sulphur is recommended but nickel is sometimes most convenient) should be used to monitor the fluence and its uniformity over the irradiated item.

In addition to the neutron fluence measurements, gamma-ray dose determinations should be made to check the n/γ ratio and to know what ionizing exposures were given. Any of the passive detectors may be used and should be corrected for neutron dose. A gamma-sensitive SEMIRAD may be used in a fission (but not a fusion) neutron spectrum for an active gamma-ray (dose rate) measurement. Also, for fission reactor work only, an active separation of neutrons and gamma rays is possible using neutron- and gamma-sensitive scintillator photodiodes, if the n/γ ratio is above 10^9 n/(cm^2$\cdot$rad).

Selective Shielding

A radiation spectrum may contain components that are undesirable for a particular experiment. To induce changes in the radiation spectrum, the experiment is usually protected by materials that selectively attenuate the undesirable radiation. Although such absorbers have a much greater effect on a particular component of the radiation spectrum, it must be remembered that they do, to a lesser extent, affect all components of the radiation, in some cases enhancing one component while removing another.

Nuclear Reactor Radiations

Nuclear reactors produce three primary classifications of radiation of concern to the TREE experimentalist – thermal neutrons, fast neutrons, and gamma rays. Unfortunately, a reactor does not always produce these radiations in the ratio that is most desirable for a particular experiment. The alternative is to screen out undesirable portions of the radiation and enhance the desirable.

Thermal neutron shielding of an experiment is usually desirable to limit the formation of undesirable radioisotopes in the materials of an experiment. Such induced radioactivity in the experiment increases the time required for an experiment to cool down to the point where it can be safely handled. In addition, protection of fast neutron foil detectors from thermal neutrons is generally necessary to minimize competing activation reactions and burnout of reaction products. Materials commonly used for this purpose are boron-10 in the form of Boral (boron carbide and aluminum) or cadmium. The most frequently used thermal neutron shield is cadmium foil, which is typically 0.040 inch thick. Cadmium has the

disadvantage that the absorption of thermal neutrons is accompanied by the emission of high-energy gamma rays, thus adding to the gamma-ray flux.

Fast neutrons are removed from the radiation spectrum by slowing them down to thermal energies – that is, by degrading their energy through multiple collisions with other nuclei until their speeds are comparable to those of the thermal motion of the nuclei of the material. The lower the atomic number of the shielding material, the more efficient the material is in slowing the speed of fast neutrons. Therefore, materials such as water, graphite, paraffin, and polyethlene are generally used for this purpose. A rough rule of thumb is that 1 foot of water reduces fast neutron flux by two orders of magnitude.

On the other hand, the efficiency with which materials absorb gamma rays increases with increasing atomic number and decreases with increasing energy of the gamma ray. For this reason, materials such as lead are used to reduce the gamma-ray flux. The attenuation of gamma rays is also an exponential function of the thickness of the absorbing material. Typically, 4 inches of lead is required to obtain an order of magnitude decrease in the gamma-ray flux in a reactor.

The measure of the quality of the radiation mixture usually used in TREE work is the ratio of the fast neutron flux [in $n/(cm^2 \cdot s)$ ($E > 10$ keV)] to the gamma-ray dose rate [in rads (Si)/s] – the n/γ ratio. In permanent radiation-damage studies, it is usually desirable to maximize the value of this quantity and thus minimize ionization and surface effects. The n/γ ratio can be enhanced by shielding the experiment with lead or another high-atomic-number material. Normally, alterations of the n/γ ratio are handled by operators of the reactor.

A word of caution: Placing such materials – or for that matter any materials – in or near a reactor can seriously affect the performance of the reactor. Check carefully with the facility technical staff when planning an experiment to make sure that the materials and techniques to be used are acceptable, and to determine what selective shielding may be necessary to produce the desired effects.

Spectral Filtering

Low-energy photons are readily attenuated in the case and packaging materials of test samples and burst detectors. This means that the spectrum at the exterior surface of a device may be somewhat different than that in the interior where the active region of the device is located (and where the photocurrents of interest are generated). This alters the relation between the dosimeter dose and the true test sample dose. Also, for a group of similar test samples exposed to the same external (to the case) environment, the inevitable differences in case thickness, material, orientation, potting, etc., would lead to an additional measure of disparity in the devices' responses which in fact would not be present in a "harder" (fewer low-energy photons) spectrum such as that of a weapon. Further, the drastic increases in mass-energy absorption coefficients at low energies make it all the more critical that the spectrum be known well in the low-energy area, although such information is seldom available.

The problem can be minimized if filters (thin metal sheets) are used to substantially reduce the low-energy photon content of a source spectrum. The problem is greatest at flash X-ray sources, the worst case of course being the low energy (300 kVp) machines.

For 600 kVp and higher energy flash X-ray machines, it is recommended that the spectra be cut off at the lower limit to about 60 keV by using a low atomic number (Z) filter or a combination of high-Z and low-Z materials. A cut-off energy of 30 keV to 40 keV is more practical for 300 kVp and 400 kVp machines since filtering is an attenuation process and to filter to energies much above 40 keV would reduce the maximum dose rate available from the low-energy machines to a practically unusable value. The filter should be interposed between the source and the sample preferably right next to the source tube.

In reporting test results, the composition, thickness, and positional sequence with respect to the source should be given for all filtering materials.

5.6 CALIBRATION

Calibration procedures are not discussed in detail in this document. However, the experimentalist should adhere to at least the following principles:

- Neutron foil calibrations can be based on known cross sections, masses of foils, and counting efficiencies calibrated with radioactive standards, or they can be related to exposures of foils to calibrated radiation sources. In either case, the calibration should be related to an NBS standard.

- Gamma dose calibrations can be related to a standardized Co-60 source, or to accurately known quantities such as specific heat of a pure material and thermoelectric voltage of a calibrated thermocouple wire. Since TREE exposures are frequently at high dose rates, the linear range of the dosimeter must be demonstrated up to the dose rates used, or else known corrections must be applied. Total dose calibrations based on Co-60 and/or calorimetry, together with linear pulse shape monitors are recommended. The experimentalist is referred to NBS for greater detail in calibration procedures.

5.7 REPORTING AND DOCUMENTATION OF RESULTS

Documentation of TREE dosimetry should be clear enough so that another experimenter can (1) repeat the measurements and perform the same analysis and (2) can apply the environmental description to another effect with possibly a different energy dependence to make a response prediction. This implies that the reporting should specify both what was actually measured and also any assumptions made in data processing.

A frequent omission in reporting is that of adequately describing the characteristics of the radiation facilities used in the experiment. Lack of this data often prevents the reader from being able to correlate the reported radiation effects to test results reported by other experimenters. All reported test results should include as a minimum the following types of facility characteristics:

- Identify the facility and where it is located.
- Specify energy levels for the radiation source.
- Specify pulse widths used, when appropriate.

- Specify distances from energy sources to irradiated samples.
- Specify any special shields and reason for use.

Neutron Environments

Because a neutron environment causes more than one TREE effect – notably, both displacement damage and ionization – it is important to measure and report environmental parameters such as fluence and spectrum rather than simply an effect parameter such as gain change in a transistor. Only then does it become possible to interpret and use fluence data accurately for other effects or at later times when all the effects (such as annealing) are better understood.

Therefore, it is recommended that the field parameters of integral fluence be reported with units of n/cm^2 having energies over the thresholds of the foils used, along with other pertinent data concerning the source and the measurement. The recommended basic reporting units are "n/cm^2 ($E >$ threshold energies for the foils used, source spectrum)" or "n/cm^2 ($E >$ 10 keV, foil used, foil/Pu ratio assumed, source spectrum)", or "n/cm^2 ($E >$ any energy, unfold code and foils used)". Differential fluence should be reported as a function of energy with units, $n/(cm^2 \cdot MeV)$ including specifications as to unfold technique and foils used.

Since neutron fluence and spectral measurements are often made with activation foil techniques, certain conventions have come into being that are considered acceptable. In particular, the sulfur-to-plutonium, (S/Pu) ratio – that is, the ratio of the fluence above 3 MeV to that above about 10 keV measured with S and Pu, respectively (with the plutonium in a standard boron shield), is a conventional way to characterize the quality of a reactor fission spectrum.

Some conventional usages are considered unclear and should be eliminated. It is preferable to state what was actually measured. Since most displacement damage by neutrons occurs at neutron energies above 10 keV it is desirable to be able to calculate, for comparative purposes, the neutron fluence in terms of $n/cm^2 (E > 10$ keV). However, it is still necessary to report what was actually measured and how the fluence, n/cm^2 ($E > 10$ keV), was determined. If a Pu foil, suitably shielded from thermal neutrons, was actually used in a pure fission spectrum, this should be stated in the dosimetry section of the report; if a sulfur pellet was used, the report should give the S/Pu ratio that was used to determine the value of n/cm^2 ($E > 10$ keV). Thus, if a Pu foil was actually used in a pure fission spectrum, the units reported as raw data should be "n/cm^2 ($E > 10$ keV, Pu, fission)"; if a sulfur foil was used, the units should be "n/cm^2 ($E > 10$ keV, S, S/Pu = (?), fission)"; and if a theoretical spectrum is being specified, "n/cm^2 ($E > 10$ keV)" is a meaningful unit. It is

recommended that the designation "fluence (foil)" always be used for the measured value, when this is meant.

Many facilities provide only sulfur dosimetry data and a single S/Pu ratio that is applied anywhere an experiment is placed. Such practices increase the inherent dosimetry error in an experiment. Since the experimenter has the responsibility, it behooves him to obtain documented information from the facility's technical staff on the currentness and accuracy of the dosimetry provided. If adequate dosimetry is not provided by the facility it is up to the experimenter to provide his own dosimetry or to obtain the dosimetry services of a reliable external source.

In determining the neutron spectrum, if a neutron spectrum is measured, report the activation foils used, the unfolding code used, the specific activity measured and the nominal cross section and threshold energies used; if a theoretical spectrum is calculated, state briefly how it was calculated giving assumptions made; and if a fission spectrum is assumed, such as the Cranberg or Watt spectrum, justify the assumption.

Once the environment has been specified and reported in a physically clear way, it is acceptable and perhaps convenient to present interpretations of these data by means of equivalence or effects units and to report how the data was interpreted and any other measurements of effects used to correlate exposures.

An effects or equivalent monoenergetic unit should then always be accompanied by a statement of:

(1) The fluences and spectrum measurements underlying it, even if these are only the measurements made by the particular facility in its own calibration work (e.g., S/Pu ratio, and a mapping)

(2) The assumptions and computational steps involved, i.e., the particular effect and its cross section vs. energy curve used, or any other means of unit conversion; e.g., for a monoenergetic equivalent, the damage constant or cross section at the chosen energy <u>must</u> be given

(3) The exact shape of the equivalence spectrum, since there are several theoretical fission spectra, as well as differences in bare critical assemblies.

Equivalent spectral units may be obtained and used in the following ways:

(1) A fluence, Φ, or "equivalent 1 MeV" [or other assumed equivalent spectrum f(E)] may be obtained from the measured spectrum, Φ_m, by the following equations. The equivalence holds for an effect described by the energy-dependent cross

section $\sigma(E)$. $\Phi_m(E)$ denotes a differential energy spectrum, Φ denotes a fluence, and $f(E)_n$ denotes a normalized differential energy spectrum.

$$\Phi_{1\ \text{Mev eq}} = \frac{\int \sigma(E)\ \Phi_m(E)\ dE}{\sigma\ (1\ \text{MeV})} , \tag{5.6}$$

or by

$$\Phi_{\text{equiv } f(E)} = \frac{\int \sigma(E)\ \Phi_m(E)\ dE}{\int \sigma(E) f(E)_n\ dE} . \tag{5.7}$$

$\Phi_m(E)$ is the differential spectrum determined by activation foils as recommended earlier.

(2) When dealing with a specific effect only, for which $\sigma(E)$ is stated, and in an environment where spectrum is relatively constant, the effects units may be a convenient means of data comparison, and reported as such, along with environmental data.

Values for $\sigma(E)$ have been calculated by several authors. Figure 5.1 is a graphical presentation of $\sigma(E)$. For practical calculations of $\Phi_{1\ \text{MeV eq}}$, the following form of equation 5.6 is to be used:

$$\Phi_{1\ \text{MeV eq}} = \frac{\sum \sigma(E_i)\Phi_m(E_i)}{96\ \text{MeV} \cdot \text{mb}}$$

where

96 MeV·mb is the value of $\sigma(E)$ at about 1 MeV

E_i is a finite energy interval

$\Phi_m(E_i)$ is the fluence of neutrons with energy in the E_i energy interval

$\sigma(E_i)$ is the average value of the cross section for the E_i energy interval

The dosimetry example for a TRIGA Reactor considers this calculation in more detail. Table 5.5 presents tabular values for $\sigma(E)$ and for $\sigma(E)$ normalized to 96 MeV·mb.

TABLE 5.5 DISPLACEMENT ENERGY TRANSFER CROSS SECTION*

Neutron Energy (MeV)	σ (E) (MeV·mb)	Normalized to 96 MeV·mb	Neutron Energy (MeV)	σ (E) (MeV·mb)	Normalized to 96 MeV·mb
0.04	7.20	0.075	1.5	92.8	0.97
0.10	9.24	0.0962	1.6	102	1.06
0.15	5.30	0.0552	2.0	130	1.36
0.18	74.8	0.779	2.2	141	1.47
0.20	116	1.21	2.6	149	1.55
0.30	65.8	0.685	2.8	130	1.35
0.44	51.6	0.537	2.9	163	1.70
0.53	56.0	0.583	3.0	109	1.14
0.57	164	1.70	3.1	148	1.54
0.60	75.6	0.787	3.3	126	1.31
0.64	63.8	0.664	3.4	140	1.45
0.70	59.8	0.622	3.65	95.7	1.00
0.76	60.0	0.625	3.8	138	1.43
0.80	181	1.89	3.9	122	1.27
0.85	91.0	0.94	4.0	155	1.61
0.88	76.8	0.800	4.15	126	1.31
0.90	119	1.23	4.25	179	1.87
0.91	108	1.12	4.4	150	1.56
0.95	146	1.52	4.5	175	1.82
0.97	151	1.58	4.6	154	1.60
1.00	120	1.25	4.75	231	2.40
1.15	51.0	0.531	5.0	154	1.60
1.16	72.0	0.75	5.1	206	2.14
1.18	65.1	0.678	5.3	158	1.65
1.19	121	1.25	5.4	153	1.59
1.21	68.2	0.710	6.0	162	1.68
1.24	102	1.06	7.0	176	1.83
1.27	60.8	0.633	8.0	202	2.11
1.30	95.7	0.996	14.0	240	2.50

*σ(E) in MeV·mb for lifetime damage in silicon, developed from a report by R. R. Holmes, et. al. See Figure 5.1.

An analytical expression which is a satisfactory fit to the curve in Figure 5.1 for 1-MeV equivalence calculations is given by:

$$\sigma_{normalized} = 1.1E\,(1 - e^{-2.2/E})$$

This is only an approximation to the relative damage curve and should only be used if the neutron spectrum is a close approximation to a fission spectrum. The person using this approximation has the responsibility for making sure that no great error is introduced by its use.

The system designer is responsible for the operation of his designed system, so he must correlate the component response data and the test environment data and the specified threat environment information. It should now be clear why use of environment parameters is recommended; that is, why the radiation physics data should be used rather than being obscured or lost by integrating them over effects curves. It is impossible to correlate effects unequivocally without environment data. The system designer should use an effects curve for the desired effect (displacement or ionization) to relate the effect of measured data test environment to the effect of the specified threat environment on the component or system.

The correlation of a measured environment, $\Phi_m(E)$, with a specified (and possibly degraded by penetration of material) environment, $\Phi_s(E)$, for an effect with energy dependence $\sigma(E)$ follows:

$$\text{Effect of test environment} = \int \sigma(E)\Phi_m(E)dE$$

$$\text{Effect of specified environment} = \int \sigma(E)\Phi_s(E)dE.$$

Comparison of these effects gives the designer information he needs.

5.7.2 Photon and Electron Environments

As discussed in Section 5.3, TREE experiments in photon environments are in general even less dependent than neutrons upon the need for high resolution spectral data, but any spectrum information available about the source should be reported. For ionization effects experiments, units of rads (experiment) or rads (experiment)/s should be used and the method used for obtaining these numbers should be reported. If the dose in rads (experiment) was computed from a measured rads (dosimeter), the method of conversion (either by evaluation of Equation 5.5 or by an approximation method) and/or assumptions made should be stated and the spectral shape utilized or assumed given. Remember, when dose in rads is reported, the material to which the energy was deposited must be specified.

If the experimental component of concern was in a configuration where electron equilibrium was not achieved, this fact should be made clear and sufficient data reported so that someone interpreting the experiment can determine the effect of this nonequilibrium on the actual dose to the component. In addition the method for achieving (or not achieving) electron equilibrium in the dosimetry materials should be reported.

The same dose units, rads (experiment), used for photon exposures can be used with electron exposures. Again both the original measurements in units of rads (dosimeter) and the technique and parameters used to convert to rads (experiment) should be reported. Corrections made for bremsstrahlung, scattering, etc., losses should also be clearly stated.

5.8 DOSIMETRY EXAMPLES

Several dosimetry examples are presented here to exemplify some of the principles presented in this section and to further enhance the understanding of what an experimenter should look for in the dosimetry of an experiment. A careful perusal of these examples will greatly enhance the inexperienced experimenter's insight into the techniques used in measuring the radiations of interest in TREE work. The reader should keep in mind that while the same principles apply, techniques can vary from facility to facility.

Bare Critical Reactor*

Consider for example an experiment conducted on a bare critical reactor, the SPR-II. This particular experiment involved the irradiation of a number of semiconductor devices in the center of the reactor glory hole. For each reactor burst, the sensitive volume of each device was wrapped with a small Ni foil for individual device dosimetry. By counting the induced Co-58 activity of each Ni foil, the neutron fluence ($E > 3$ MeV) to which each device was exposed would be determined.

*This example was furnished by Dr. J. V. Walker of the Sandia Corporation, Albuquerque, New Mexico.

To determine the total neutron fluence to which each device was exposed, another experiment was conducted in which the device experiment was placed in a position in the glory hole identical to the earlier exposures, along with a series of threshold foils. The foil results of this experiment are shown in the following tabulation. The foil activities, R_i, were used with the SPECTRA Code to obtain the differential energy spectrum shown in Figure 5.5. Also shown in Figure 5.5 is the integral of the differential spectrum. From these fluence data it was determined that 11 ± 1 percent of the neutrons had E > 3.0 MeV. Hence to obtain the total fast fluence to which each device was exposed, their Ni fluences (E > 3.0 MeV) were multiplied by 9.09 $\left(\text{ratio of } \frac{\text{total fast fluence}}{\text{fluence } (E > 3 \text{ MeV})}\right)$. On the same experiment, plastic scintillator photo diodes were used to determine the time dependence of the neutron exposure. Figure 5.6 shows data for three different intensity bursts.

Activation Foils	Specific Activity, R_i	Nominal Threshold Energy, E_{th}	Normalized Fluence Above E_{th}	$\bar{\sigma}$, barns
Pu^{239}(n, f)	$(9.3 \pm 0.9) \times 10^{11}$ fiss/g	10 keV	1.0	1.78
Np^{237}(n, f)	$(5.9 \pm 0.6) \times 10^{11}$ fiss/g	0.6 MeV	0.71±0.08	1.62
U^{238}(n, f)	$(8.0 \pm 0.8) \times 10^{10}$ fiss/g	1.5 MeV	0.27±0.03	0.55
Ni^{58}(n, p)Co	$(8.4 \pm 0.3) \times 10^{5}$ dpm/g*	3 MeV	0.11±0.01	0.485

*dpm = disintegrations per minute.

From this example, the following dosimetry procedures are illustrated:

(1) The use of threshold foils to determine a neutron differential and integral energy spectrum. The foils were exposed in the geometry of interest, counted, and the absolute specific activities (dpm/gm) were determined from the known counter efficiencies. These activities were in turn used with an unfold code to solve Equation 5.1 to determine $\phi(E)$. (Equation 5.1 is written for each detector and the set solved simultaneously and iteratively by the SPECTRA Code.)

(2) The determination of an average cross section for a threshold detector in a known spectrum. The spectrum $\phi(E)$ found above was used with Equation 5.4 to find the spectral averaged Ni cross section $\bar{\sigma} = 485$ mb.

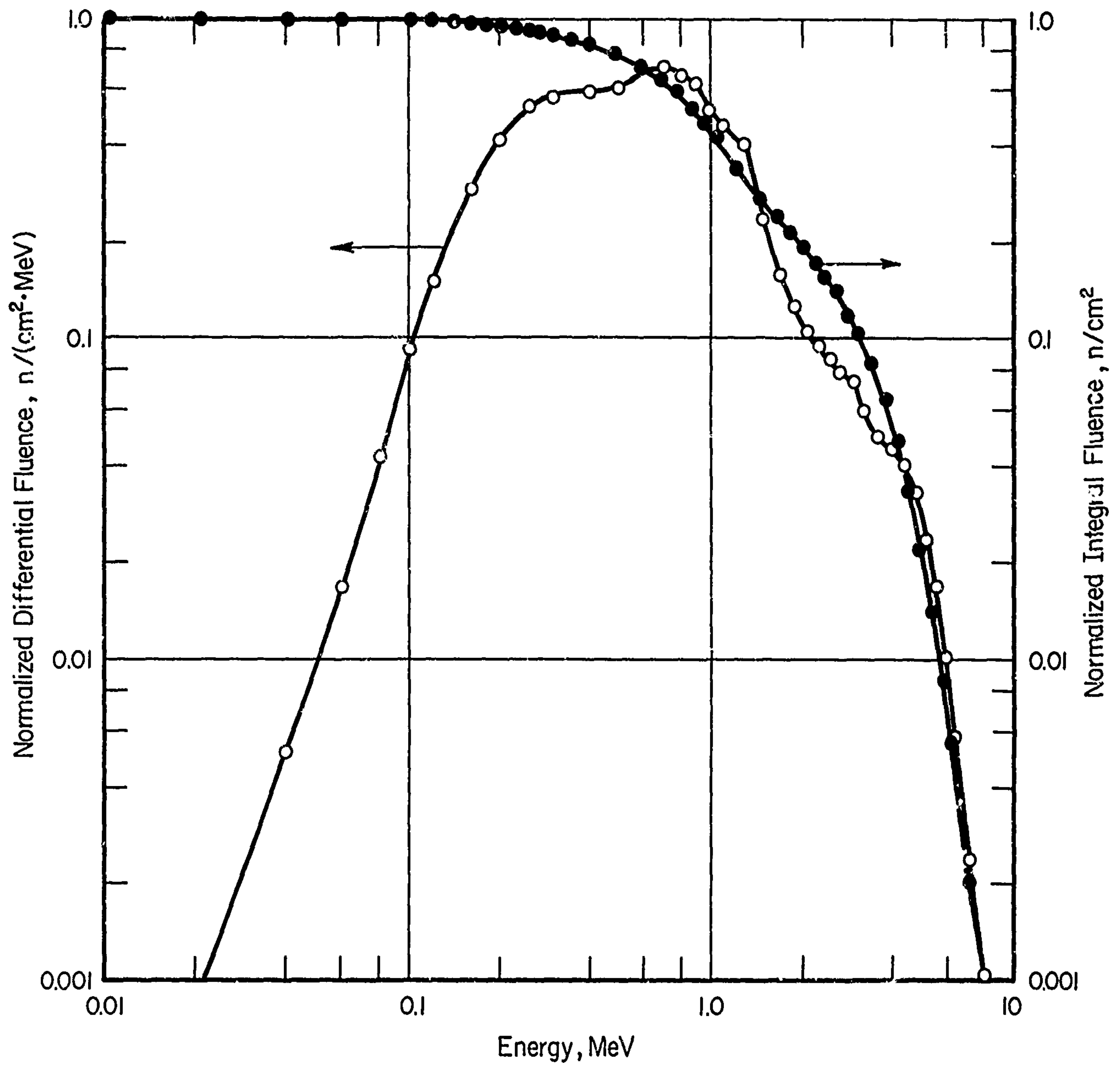

FIGURE 5.5. DIFFERENTIAL AND INTEGRAL NEUTRON [illegible] SPECTRUM IN THE SPR II GLORY HOLE

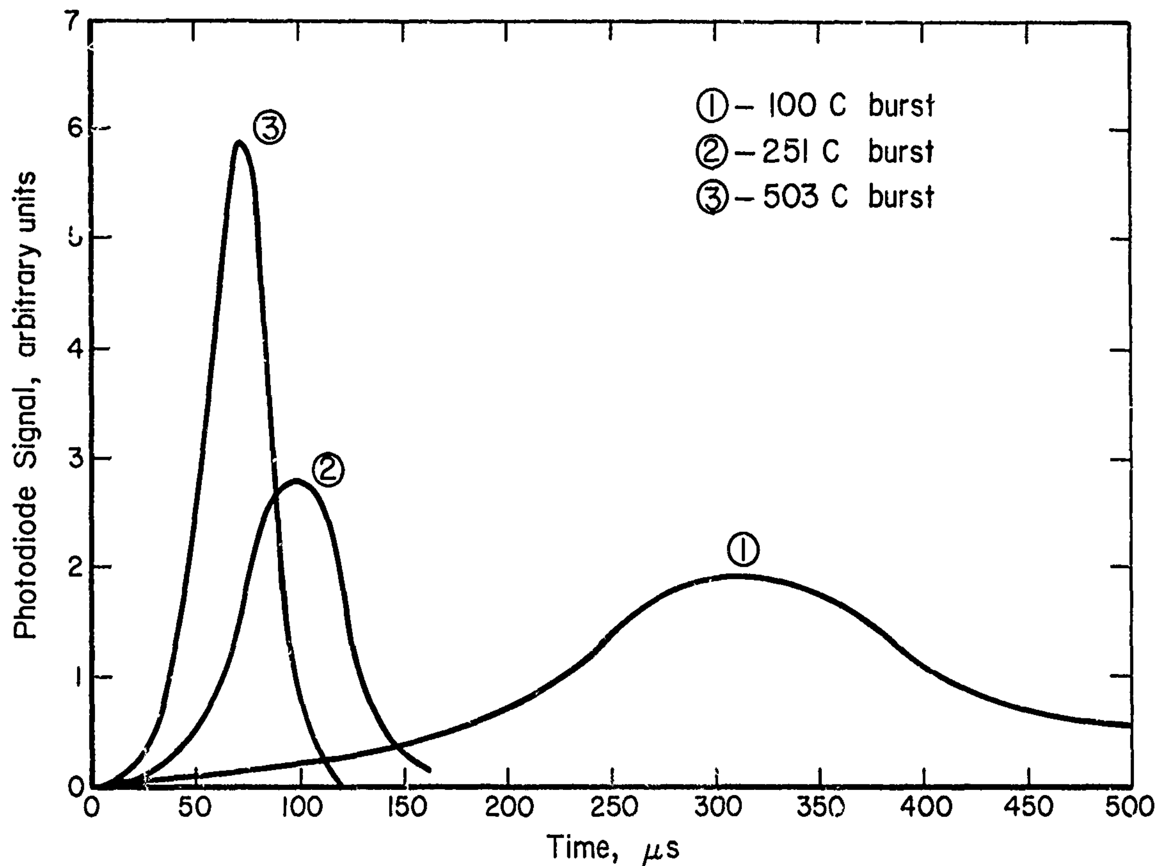

FIGURE 5.6. SPR-II BURST TIME PROFILES FOR VARIOUS SIZE BURSTS AS DETERMINED WITH A PHOTODIODE

(3) The use of a spectral averaged cross section and individual dosimeter foils to determine the neutron fluence to which each device was exposed. With an average cross section of $\bar{\sigma}$ = 485 mb, each Ni specific activity (dpm/gm) was converted to fluence (E > 3.0 MeV), i.e.,

$$\int_{3.0\ \mathrm{MeV}}^{\infty} \phi(E)dE = \frac{(\mathrm{dpm/g}\ A\ T_{1/2}}{0.693\ N_o\ \bar{\sigma}}$$

where A is the foil's atomic weight, N_o is Avagadro's number, and $T_{1/2}$ is the foil's half life. The total fast fluence was found from these data and the integral fluence results obtained from the unfold code; i.e.,

$$\int_{10\ \mathrm{kV}}^{\infty} \phi(E)dE = 9.09 \int_{3.0\ \mathrm{MeV}}^{\infty} \phi(E)dE.$$ (9.09 for Ni in SPR-II glory hole).

(4) Neutron exposure rates for each device were determined from the total fluence values obtained from the steps above and the time resolved data obtained from the fluor-photodiode measurements.

(5) The radiation effect being studied was predicted from the known damage response function (see, e.g., Figure 5.1) and the measured neutron energy spectrum. That is, Equation 5.3 was evaluated and the resultant predicted damage was compared to that measured for each device tested.

In this experiment the gamma-ray dose was not of interest, was known to be insignificant from previous measurements, and hence was not remeasured. If the gamma-ray dose had been of interest it would have been measured with a PIN diode, applying a small correction for neutron sensitivity.

TRIGA Reactor*

TRIGA Reactor J-Tube Dosimetry

At Gulf Radiation Technology's Advanced TRIGA Prototype Reactor (ATPR) facility, one of the sample radiation positions is called the J-tube. This is a large rectangular tube which extends from the top of the reactor pit into the reactor core. A diagram of the J-tube in position is shown in Figure 5.7, while Figure 5.8 shows the relationship of the nose of the tube to surrounding fuel elements. The neutron flux and gamma dose at this location, as a function of reactor operating power level, were established by fission-foil and TLD measurements.

The dosimetry was performed by EG&G personnel with fission foils encased in boron balls as well as with sulfur foil dosimeters. Several runs were made with slight changes in boron ball position. These separate measurements were necessary so that fluences measured at any one location would not be altered by the presence of another boron ball nearby. No sulfur pellets were irradiated within two diameters of any boron ball. The gamma-ray dose was measured with a CaF thermoluminescent detector calibrated in rads (Si).

The results of the boron-ball-fission-foil measurements are shown in Figure 5.9, and the sulfur dosimeter results in Figure 5.10. The averages of fission-foil and activation-foil values are listed in Table 5.6.

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*This section and the following one on the LINAC dosimetry example were prepared by Mr. John W. Harrity of Gulf Radiation Technology, San Diego, California.

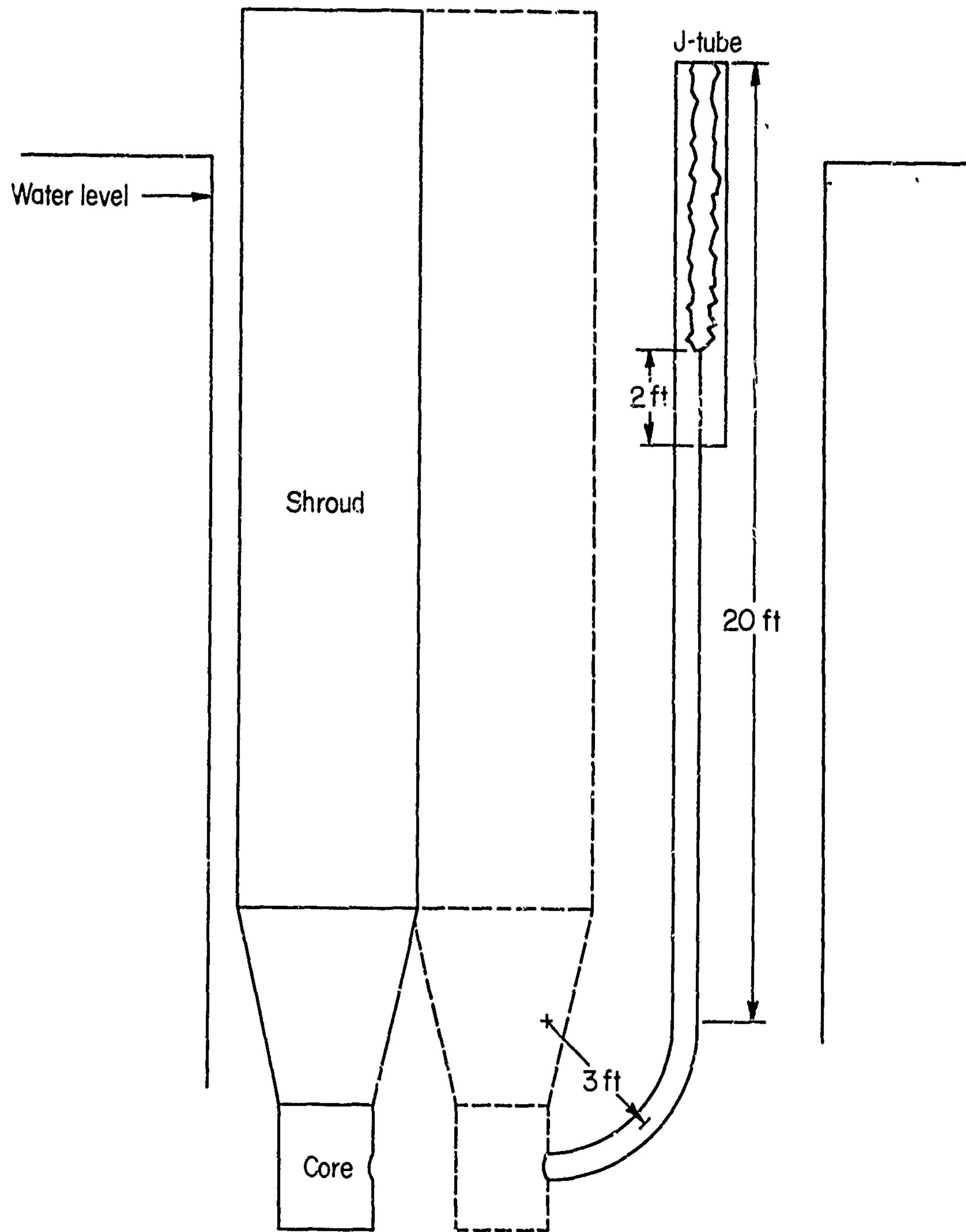


FIGURE 5.7. DIAGRAM OF J-TUBE IN POSITION IN ADVANCED TRIGA PROTOTYPE REACTOR

FIGURE 5.8. ATPR J-TUBE POSITION IN CORE

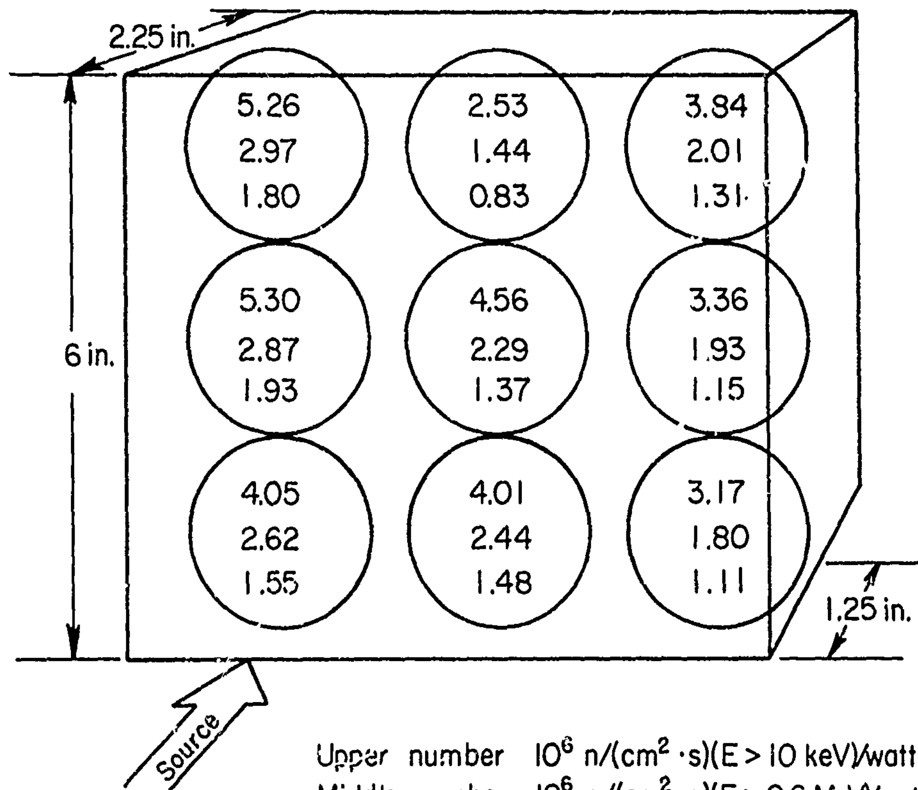


FIGURE 5.9. RESULTS OF BORON-BALL FISSION-FOIL MEASUREMENTS

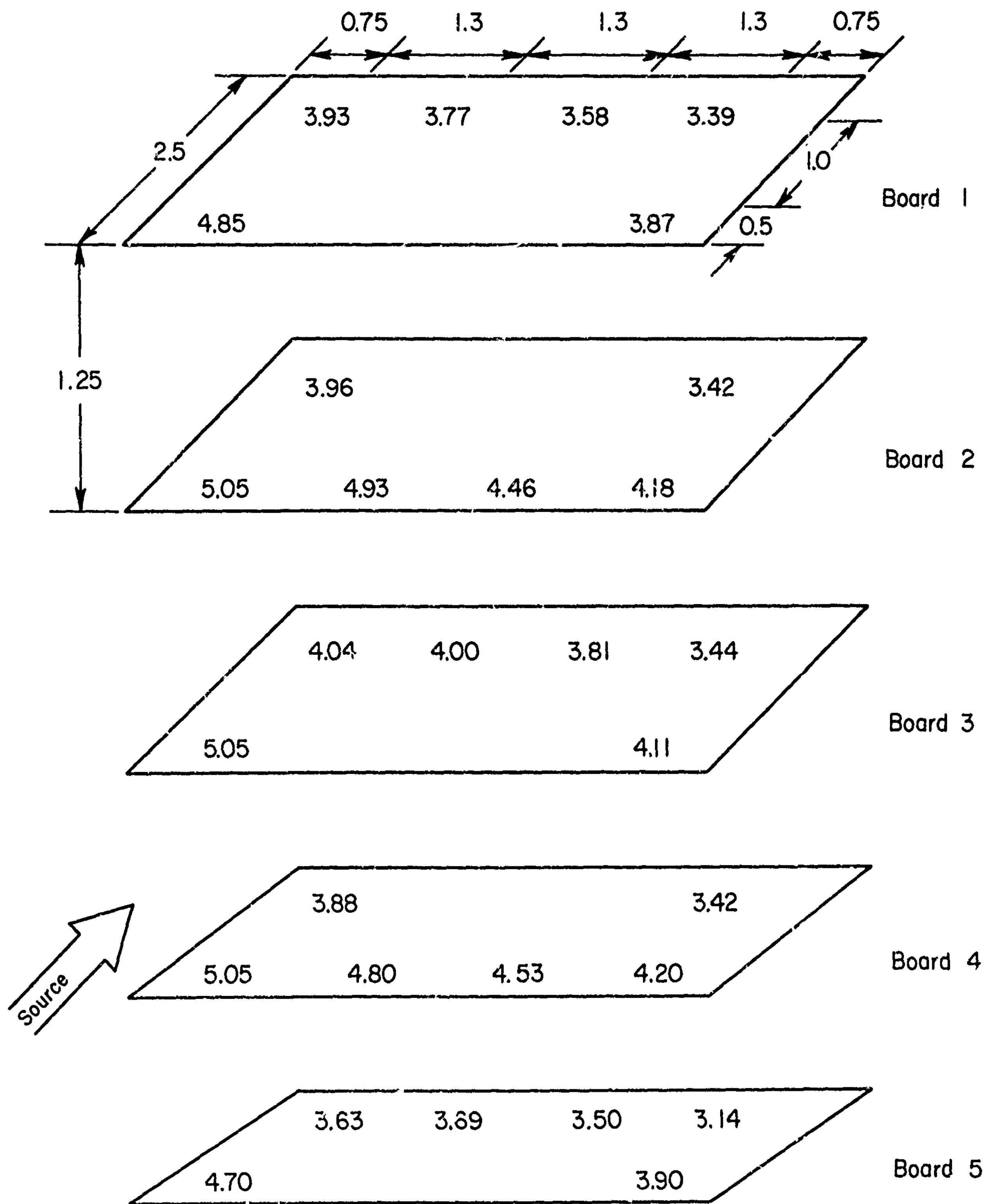


FIGURE 5. 10. ATPR J-TUBE CARRIAGE DOSIMETRY

Sulfur foil readings in units of 10^5 n/(cm^2· s) (E > 3 MeV)/watt.

Dimensions in inches.

TABLE 5.6. FISSION-FOIL MEASUREMENTS IN ATPR J-TUBE

Neutron Energy	n/(cm^2.watt)
E > 10 keV	4.0×10^6
E > 0.6 MeV	2.3×10^6
E > 1.5 MeV	1.4×10^6
E > 3.0 MeV	4.1×10^5
Gamma [rads (Si)/s·watt]	8.1×10^{-3}

This crude spectrum measurement was used to normalize a more detailed calculated spectrum*, listed in Table 5.7.

All of these values were calculated using the system of reactor analysis codes developed by Gulf Radiation Technology and the DSN transport code of the Los Alamos Scientific Laboratory.

The F-ring spectrum was used as the most appropriate to the J-tube location, and energies below 10 keV were neglected. Based on this spectrum as normalized to the fission-foil data, a "1-MeV-equivalent" value can be obtained. This equivalence unit is defined in terms of the displacement damage in bulk silicon. The fluence of 1-MeV monoenergetic neutrons that would be required to produce the same specific amount of damage as that caused by a given fluence of the TRIGA reactor spectrum is the 1-MeV equivalent fluence. The purpose of using such a unit is to be able to relate displacement effects damage to silicon obtained in tests performed at one facility to those experienced at another facility with a different neutron spectrum.

The 1-MeV-equivalent value is found by integrating the product of neutron fluence and normalized displacement-damage cross section over all values of neutron energy, E > 10 keV. The normalized displacement-energy-transfer cross section is shown in Figure 5.1; this cross section was normalized to the value at about 1 MeV, 96 MeV·mb. (See Section 5.7).

The results of this integration are shown in Table 5.8. From these values, it can be calculated that the 1-MeV equivalent to E > 10 keV ratio at this position in the reactor is 0.87, and the 1-Mev equivalent to E>3 MeV ratio is 8.5. Thus if sulfur foils are used for dosimetry, the equivalent fluence is 8.5 times the sulfur reading.

*West, G. B., "Calculated Fluxes and Cross Sections for TRIGA Reactors", Report GA-4361, Gulf General Atomic (August 14, 1963).

TABLE 5.7. ONE-DIMENSIONAL FLUXES FOR THE 1-MW TRIGA REACTOR (WATER REFLECTED)

Average Neutron Flux over 15-in. Core Height; Fuel Temperature, 200 C; Water Temperature, 23 C; 87 Fuel Elements ($U-ZrH_{1.7}$)

[$\times 10^7$ n/(cm^2·s·watt)]

Group	Δu	Energy Range	Position in Core: Core Center (r=0.0 cm)	Position in Core: D Ring[a] (r=12 cm)	Position in Core: F Ring (r=20 cm)	2 cm Beyond Core[b] in H_2O
1	0.25	10.-7.79 Mev	0.0094	0.0069	0.0033	0.0017
2	0.25	7.79-6.07 Mev	0.0269	0.0198	0.0096	0.0046
3	0.25	6.07-4.72 Mev	0.0595	0.0438	0.0211	0.0098
4	0.25	4.72-3.68 Mev	0.0972	0.0715	0.0345	0.0149
5	0.5	3.68-2.23 Mev	0.321	0.236	0.114	0.0488
6	0.5	2.23-1.35 Mev	0.386	0.284	0.135	0.0527
7	0.5	1.35-0.821 Mev	0.361	0.265	0.126	0.0472
8	0.5	0.821-0.498 Mev	0.299	0.220	0.103	0.0404
9	1.0	0.498-0.183 Mev	0.392	0.288	0.135	0.0545
10	1.0	183-67.4 kev	0.252	0.185	0.0862	0.0370
11	1.0	67.4-24.8 kev	0.186	0.137	0.0633	0.0282
12	1.0	24.8-9.12 kev	0.159	0.117	0.0542	0.0247
13	2.0	9.12-1.23 kev	0.286	0.210	0.0973	0.0464
14	2.0	1.23-0.167 kev	0.270	0.198	0.0919	0.0467
15	2.0	167-22.6 ev	0.261	0.192	0.0893	0.0472
16	2.0	22.6-3.06 ev	0.241	0.177	0.0830	0.0465
17	1.12	3.06-1.0 ev	0.131	0.0963	0.0454	0.0255
18	0.43	1.0-0.65 ev	0.0566	0.0416	0.0196	0.0112
19	0.44	0.65-0.42 ev	0.0601	0.0441	0.0209	0.0120
20	0.48	0.42-0.26 ev	0.0793	0.0583	0.0283	0.0140
21	0.62	0.26-0.14 ev	0.214	0.157	0.0834	0.0440
22	0.85	0.14-0.06 ev	0.599	0.440	0.247	0.298
23	0.84	0.06-0.026 ev	0.491	0.361	0.205	0.393
24		0.026-0 ev	0.244	0.179	0.102	0.253

(a) D ring is approximate location of the average core flux.

(b) Position of peak thermal flux in reflector.

TABLE 5.8. DAMAGE FACTOR CALCULATIONS

ΔE	J-Tube, $\times 10^7$ n/(cm^2·watt)	Average Damage Factor in this Interval	1-MeV Equivalent, $\times 10^7$ n/(cm^2·watt)
10.0 - 24.8 keV	0.0233	0.058	0.0013
24.8 - 67.4 keV	0.0285	0.076	0.0022
67.4 - 183 keV	0.0392	0.136	0.0053
0.183 - 0.498 MeV	0.0612	0.68	0.0416
0.498 - 0.821 MeV	0.0468	0.89	0.0416
0.821 - 1.35 MeV	0.0572	1.00	0.0572
1.35 - 2.23 MeV	0.0613	1.20	0.0736
2.23 - 3.68 MeV	0.0518	1.39	0.0720
3.68 - 4.72 MeV	0.0157	1.49	0.0234
4.72 - 6.07 MeV	0.0096	1.77	0.0170
6.07 - 7.79 MeV	0.00436	1.87	0.0082
7.79 - 10.0 MeV	0.0015	2.17	0.0032
	0.4005		0.3466

TRIGA Reactor In-Core Dosimetry

One of the positions in the TRIGA reactor in which samples are frequently irradiated is in-core. This is accomplished by removing a fuel element in the core, inserting a drift tube into the fuel element position, and lowering the samples to be irradiated down the drift tube. The space for such irradiations limits samples to those which can be mounted in a 1-1/4-in.-diameter sample holder; many samples must be mounted vertically within the holder. A measurement was made of the distribution of neutron flux over the 14-in. height of the core.

As the diameter of the site prohibits the use of standard boron-ball fission-foil measurements, the spectrum at a given core location is taken from theoretical calculations and normalized to activation-foil measurements. The calculation for converting sulfur foil readings to 1-MeV equivalent fluence is performed as above, using the theoretical spectrum.

For measurement of the flux distributions in the D-ring of the TRIGA Mark I reactor, both sulfur and nickel foils were used. The sulfur foils were read by EG&G personnel, and the nickel foils were counted locally and normalized to the sulfur readings. Figure 5.11 shows the distribution of flux vertically through the core as determined by these measurements.

Linear Accelerator (LINAC)

The dose delivered at a specific location by a linear accelerator can be measured using any one of several passive devices – cobalt glass, Ag-PO_3 glass, LiF or CaF thermoluminescent detectors, etc. However, this is a very time-consuming and arduous technique if a dose delivered in individual pulses is desired because the dosimeter would have to be changed before each pulse.

In place of this, an active measurement of each pulse is usually made which displays on an oscilloscope a time-resolved trace representative of the current in the pulse. The integral of this beam current pulse is proportional to the dose delivered to the sample under test. A calibration of the observed signal against a measured dose delivered at the sample location is required to obtain useful dose information from the active display.

Different methods may be used to obtain the current signal. One method is to mount a stopping block behind the irradiated material and monitor the voltage developed across a resistor as the stopped charge leaks off to ground. Another method is to collimate the beam and direct it through the loop of a current transformer coil. Still another technique involves the use of a secondary emission monitor (SEM). This consists of a thin metal foil mounted in an evacuated chamber through which the collimated beam passes before impinging on the sample. In this case, the

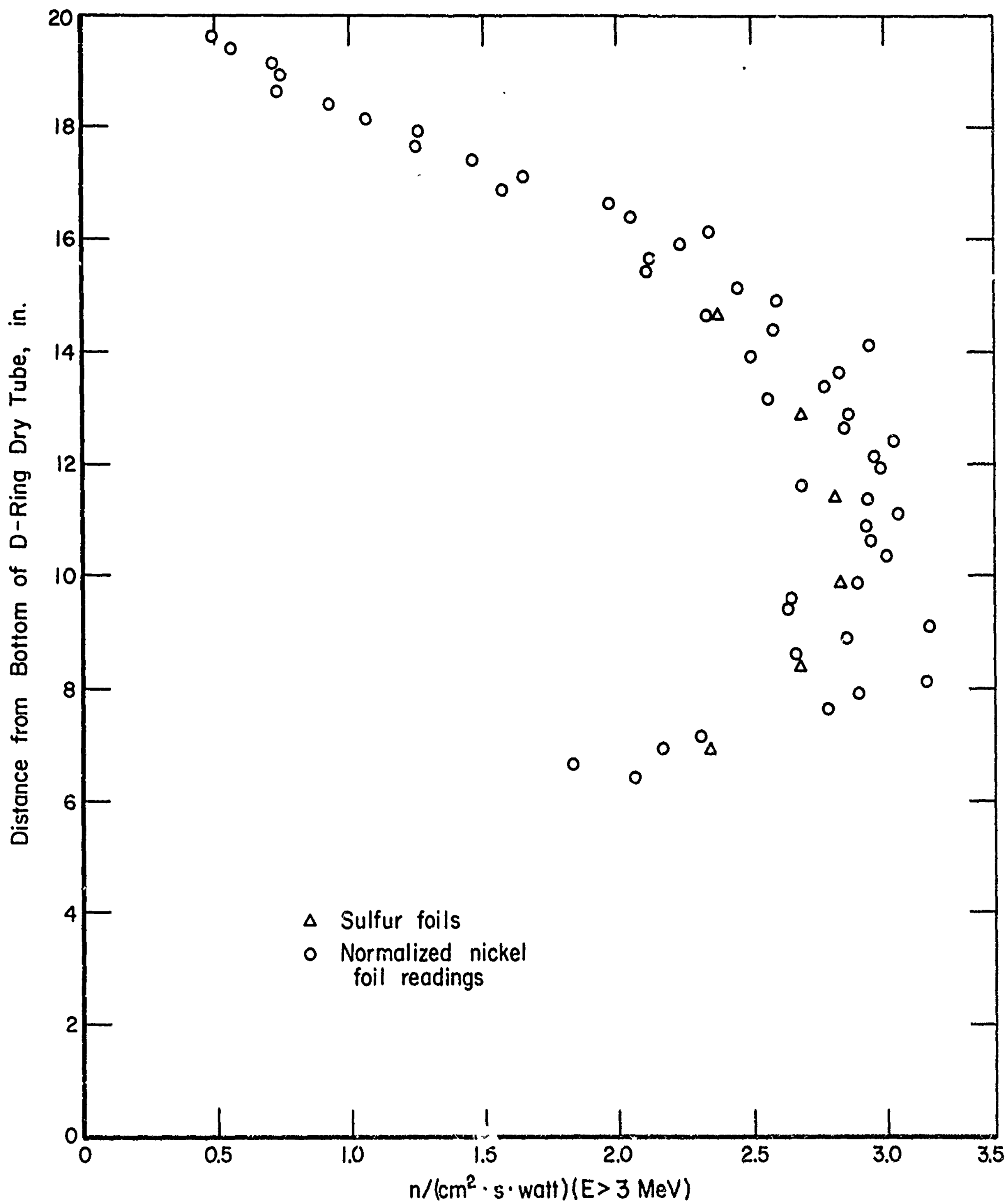


FIGURE 5.11. DISTRIBUTION OF FLUX VERTICALLY THROUGH TRIGA REACTOR AT THE D-RING

quantity measured is the current flowing from ground to replace the electrons knocked from the foil by the incident beam.

Again, the dose delivered at the sample location for calibrating the current pulse may be measured by one of the passive devices mentioned above. Alternate active measurement techniques, however, are available which yield more immediate results. One device which yields the dose deposited in a given material directly is a thin calorimeter. A thermocouple attached to a block of the material of interest, which is thin compared to the range of the electrons in this material, is used to measure the temperature rise in the material due to a single pulse. The energy deposited in the material is then obtained using the specific heat of the material.

At Gulf Radiation Technology, the beam current monitor used is an SEM, and one active dosimeter used is a thin calorimeter using a copper block (0.1 x 0.1 x 0.020 in.) and a copper-constantan thermocouple. The copper block is mounted in a water-cooled chamber, with entrance and exit windows of 1-mil Mylar foil, which is evacuated during the test to improve the thermal isolation of the block. The copper-constantan thermocouple is made of 3-mil thermocouple wire soldered to the block with a minimum of solder. The chamber is mounted at the test location and the SEM output is calibrated against the measured dose. For added convenience in reducing data, the beam current pulse is electrically integrated and the integrated signal is calibrated against dose.

Figure 5.12 shows samples of the beam pulse output of the SEM, the integrated beam pulse output, and a recorder trace of the thermocouple response. Using these data, the calibration of the SEM for this location was performed as follows:

T. C. signal $(\Delta V) = 19\ \mu V$

T. C. sensitivity $(\Delta V/\Delta T)_{Cu-const} = 40\ \mu V/{}^\circ C$

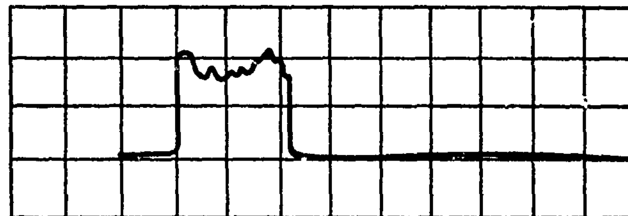
Cu specific heat $C = 0.092$ cal/g/°C

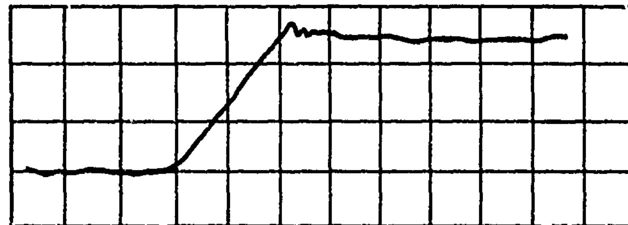
$$\text{Dose} = \frac{19\ \mu V \times 0.092\ \frac{cal}{g^\circ C} \times 4.19 \times 10^7\ \frac{erg}{cal}}{40\ \frac{\mu V}{^\circ C} \times 100\ \frac{erg}{g\text{-}rad}} = 1.83 \times 10^4 \text{ rads (Cu)}$$

Int. SEM signal $(\Delta V)_{SEM} = 5.2$ Int. V

$$\text{Calibration factor} = \frac{\text{Dose}}{\Delta V_{SEM}} = \frac{1.83 \times 10^4}{5.2} = 3.52 \times 10^3 \text{ rads (Cu)/Int. V.}$$

Thus, for every volt of integrated secondary emission signal, 3.52×10^3 rads (Cu) is deposited at the test location. Since for most cases of interest it is preferred that the dose be reported in rads (Si), this dose in copper is





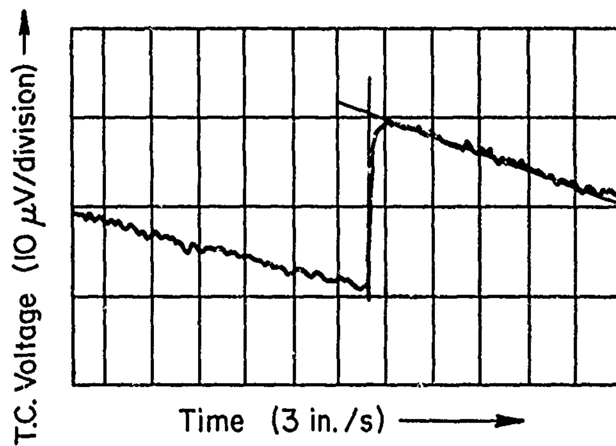


FIGURE 5.12. SAMPLES OF DATA USED TO CALIBRATE DOSE DELIVERED BY LINEAR ACCELERATOR

multiplied by the ratio of most probable energy losses in the two materials (essentially, the Z/A ratios).* This results in

$$3.52 \times 10^3 \frac{\text{rads (Cu)}}{\text{Int. V}} \times 1.17 = 4.12 \times 10^3 \frac{\text{rads (Si)}}{\text{Int. V}}$$

Another active device frequently used in place of the thin copper calorimeter is a thermistor. The thermistor is mounted in a small vacuum chamber identical to that in which the copper block is mounted, and is used in the same way. The thermistor forms one leg in a Wheatstone bridge circuit, and the transient unbalance voltage of the bridge is monitored. The circuit for this is shown in Figure 5.13.

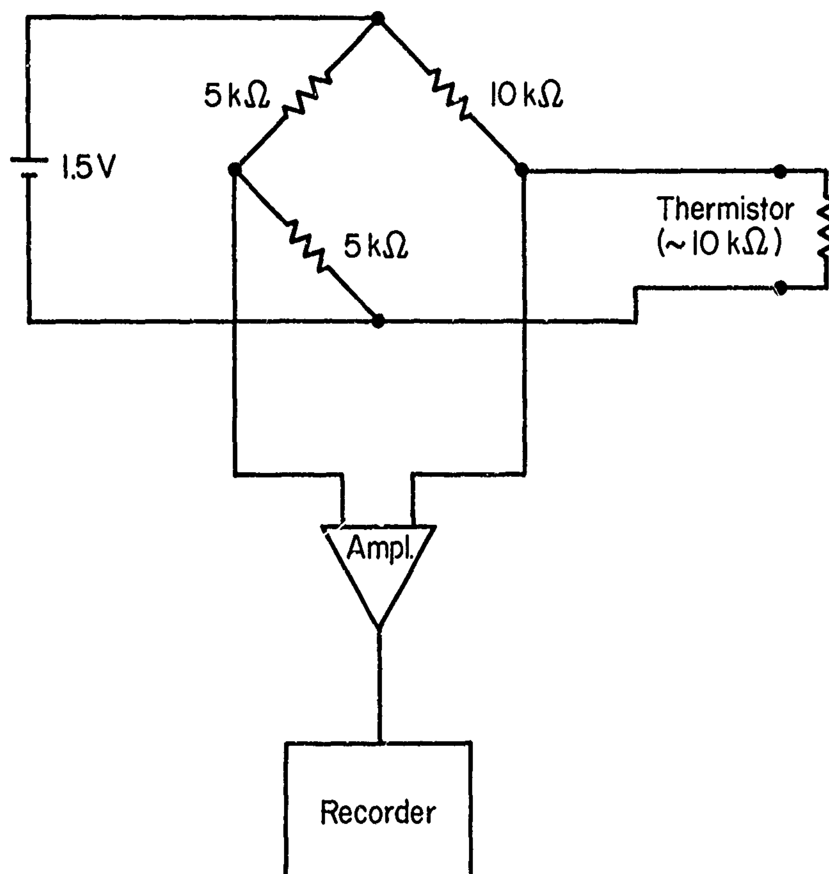


FIGURE 5.13. THERMISTOR-WHEATSTONE BRIDGE DOSIMETER CIRCUIT

*A silicon block could be used instead of a copper block, but the temperature rise in the thermocouple leads is close to that in the copper and an equilibrium time would be required for them to come to the temperature of the silicon block. Also, because the specific heat of silicon is higher than that of copper, the output signal would be smaller.

As thermistor material is a mixture of refractory oxides, the exact specific heat is not necessarily a constant from thermistor to thermistor and may vary under prolonged irradiation. Therefore, this device must be calibrated periodically against a standard. The primary reason for using this active dosimeter is that it is approximately 400 times as sensitive as the copper-block calorimeter, permitting calibration to be performed at much lower doses.

Flash X-Ray Machine*

The HDL 5 megavolt flash X-ray facility is operated in either electron beam or X-ray mode. The chief methods of dosimetry used for each mode are described.

Electron dosimetry is usually a part of the experimental package and has been predominantly of the thin in-line calorimeter type. The calorimeter is a thin sheet of metal (e.g., aluminum, copper, or tantalum a few mils thick) that is placed between the sample and the source of the electron beam. The calorimeter material absorbs some of the beam's energy, raising its temperature above ambient. A thermocouple spot welded to the metal sheet is used to record the temperature rise, which is proportional to the average energy absorbed by the calorimeter. These data, combined with energy deposition profiles of calorimeter and target material or materials are used to determine the exposure and, in turn, the energy absorbed by the target materials.

The energy deposition profiles can be obtained with computer codes such as the electron transport code ZEBRA or by experimental measurements. In some cases the profiles are obtained experimentally with multiple layered calorimeters but, in general, the computer codes are more convenient. For the ZEBRA code, the energy spectrum of the electron beam and material properties such as the stopping power and density are required inputs.

The X-ray dosimetry consists of EG&G types TL-32 and TL-35, CaF_2 thermoluminescent dosimeters (TLD's) in energy linearizing shields, and a reader. The shields compensate for the over-response of CaF_2 to lower energy (below 1 MeV) X-rays.

Calibration of the TLD's was accomplished with small cobalt-60 and cesium-137 point sources. The activities of these gamma sources were referenced to NBS standards by use of a Victoreen R-meter.

The TLD's exhibit repeatability as individuals to within a 2 percent spread. As a group, the TLD's have a normal distribution about a mean

*This example was furnished by Dr. J. D. Silverstein of the Harry Diamond Laboratories, Washington, D. C.

response. Elimination of individuals with the greatest deviations lowered the fractional standard deviation to ± 5.5% (one σ). This process is a compromise between accuracy and economy. In this example, about 1/3 of the type TL-32 TLD's were diverted to other applications.

Since σ represents 68% of the TLD population, the probability of selecting a detector which is within ± 5.5% is .68 in this example. 2.6 σ represents 99% of the population. Therefore, ± 14.3% is expected as a "worst accuracy" in a random choice from a box of calibrated TLD's.

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6.0 TEST PROCEDURES FOR DIODES AND TRANSITORS

6.1 PERMANENT-DEGRADATION MEASUREMENTS

Scope

This section deals with experimental procedures for determining the degree of semipermanent and permanent degradation of specific parameters of conventional discrete bipolar transistors, MOS and junction field-effect transistors, semiconductor diodes, and Zener diodes. The procedures outlined are intended for use in mixed neutron-gamma or gamma radiation environments. Extrapolation of the procedures set forth here for application to other devices and/or other kinds of radiation should be performed with great care. The recommended procedures that follow have been found to be valid for neutron fluences and gamma doses at least as great as 10^{15} n/cm^2 (E > 10 keV, fission) and 10^8 rads (Si), respectively.

Bulk and Surface Effects

Permanent effects of a mixed neutron-gamma field can be grouped into bulk and surface damage. Carrier-removal and lifetime damage caused by radiation-induced lattice displacements are important categories of bulk damage. Lifetime damage and carrier removal are important failure mechanisms in diodes, bipolar transistors, and junction field-effect devices. The buildup of surface charge and the creation of new interface states caused by the deposition of radiation dose are important surface effects. Buildup of space charge and creation of interface states are the primary failure mechanisms in MOS transistors. Surface effects are also important mechanisms of device failures in diodes, bipolar transistors, and junction field-effect devices. For example, the low-current transistor gain degradation due to surface effects (especially for high-gain, high-frequency transistors) can constitute a significant portion of the total gain degradation in a mixed neutron-gamma environment. Damage to semiconductor devices exposed to gamma radiation is primarily due to surface effects. High energy gamma radiation also introduces bulk damage similar to neutron damage at high doses [> 10^6 rads (Si)]. In any particular experiment, the effects of both bulk and surface damage must be considered. For example, the total gain degradation of a transistor can be expressed as

$$\left(\Delta \frac{1}{h_{FE}}\right)_{Total} = \left(\Delta \frac{1}{h_{FE}}\right)_{Bulk} + \left(\Delta \frac{1}{h_{FE}}\right)_{Surface} ,$$

where $\Delta 1/h_{FE}$ is the change in reciprocal current gain. Similar expressions can be written for the other parameter changes. A summary of the effects of radiation on device parameters is listed in Table 6.1. The table indicates the relationship between the radiation-induced bulk and surface effects and important device parameters.

In cases where both bulk and surface damage are expected to be important, experiments should be conducted in both a mixed neutron-gamma (high n/γ) and a pure gamma environment and the effects of bulk and surface damage analytically separated. In cases where bulk damage is the predominant effect, a neutron (high n/γ) environment should be used. In cases where surface damage is the predominant effect, a pure gamma environment should be used.

The reader should be aware that this section is concerned only with experimental techniques for determining radiation response of devices. However, there are analytical techniques for predicting radiation-induced damage in semiconductor devices. These analytical techniques may prove to be applicable under the following circumstances:

(1) When an estimate of parameter degradation must be made in preparation for testing

(2) When less accurate results will suffice for design data

(3) When testing must be limited, but additional data are required.

In general the effects of radiation-induced bulk damage are reasonably predictable. Unfortunately the effects of radiation-induced surface damage are not so amenable to prediction. Analytical techniques for predicting semiconductor-device parameter changes in a radiation environment have been developed on the basis of the relationship between lifetime damage, carrier removal, and neutron fluence. Methods also are available to extend limited test results to obtain a better characterization of the radiation response of a particular device. Details of these techniques are not presented here; rather, the reader is directed to the TREE Handbook and other documents cited in the bibliography for further information.

Annealing

The radiation-induced parameter changes in semiconductor devices exhibit annealing that is a function of temperature, time, and operating conditions during both irradiation and measurement. Both bulk and surface damage in semiconductor devices can be significantly annealed by injecting carriers during irradiation or during measurement, or by raising the temperature of the device.

TABLE 6.1. SUMMARY OF PERMANENT AND SEMIPERMANENT EFFECTS OF RADIATION ON DEVICE PARAMETERS

Phenomenon \ Device		Junction Diodes	Bipolar Transistors	MOS Field Effect Transistors	Junction Field-Effect Transistors
Bulk effects	Lifetime damage	Reverse-current increase Change in switching parameters Increase in forward voltage (PIN diodes)	h_{FE} decrease at all current levels Reverse-current increase Change in switching parameters	Reverse-current increase	Reverse-current increase
	Carrier removal	Increase in forward voltage Breakdown-voltage change (Zener)	Increase in $V_{CE(SAT)}$, $V_{BE(SAT)}$ h_{FE} decrease at high current levels	I_{DSS}, g_m decrease Threshold-voltage change	I_{DSS}, g_m decrease Change in pinch-off voltage Noise figure increase
Surface effects	Space charge	Reverse-current increase Breakdown-voltage change	h_{FE} decrease at low current levels Reverse-current increase Breakdown-voltage change	Threshold-voltage change Reverse-current increase Breakdown-voltage change	Reverse-current increase Breakdown-voltage change
	Interface states	Reverse-current increase	h_{FE} decrease at low current levels Reverse-current increase	g_m decrease Threshold-voltage change Reverse-current increase	Reverse-current increase Noise-figure increase

The prompt annealing process, as measured by device parameter changes as a function of time, is termed "rapid" or "transient" annealing. This process is most dramatically evidenced by an initial reduction in transistor current gain followed by a partial recovery, all within a small fraction of a second. The initial reduction in gain can be equivalent to that associated with a fluence many times as large as that actually measured. The characteristics of rapid annealing are a function of device type, temperature, and the operating conditions during irradiation. To measure rapid-annealing effects, it is necessary to irradiate the device with a neutron pulse short compared with the earliest time of interest and to operate the device actively during and after irradiation. A pulsed reactor can best be used for this type of test. In designing a rapid-annealing experiment, the experimentalist should also be aware that surface damage introduced by ionizing radiation can also undergo rapid annealing. Semiconductor devices exhibit an additional recovery trend along a scale of hours or days following irradiation. This is termed long-term annealing* and is a definite function of temperature.

At this time the detailed mechanisms of annealing are not completely understood; however, a large body of information has been compiled on both rapid and long-term annealing of bulk and surface damage. Preferred procedures for use in rapid-annealing experiments in a mixed neutron-gamma environment are given in this section under "Specific Test Procedures". Preferred procedures are not yet established for measuring rapid annealing of surface damage.

Since radiation damage is subject to annealing, the importance of keeping accurate records of time, temperature, and operating conditions during and after irradiation cannot be overemphasized. Therefore, it is recommended that the time after irradiation be recorded for each electrical measurement and that a record of measurements and temperature history for each irradiated device be maintained.

Radiation-Source Considerations

Radiation sources normally used to determine the permanent radiation damage of semiconductor devices include pulsed nuclear reactors, steady-state nuclear reactors, and low-dose-rate gamma sources. Other sources of neutrons such as fast-neutron generators, van de graaff machines, linear accelerators, and synchrotrons are sometimes used in radiation-effects studies. The reader is referred to Section 4 for a discussion of radiation-source considerations.

Regardless of the particular test technique chosen, adequate dosimetry (including energy spectrum) for each group of samples is of prime importance. It should be emphasized that adequate dosimetry during reactor

*Rapid annealing is usually considered completed in about the first 1000 seconds after irradiation.

irradiations includes gamma-dose measurements. General dosimetry techniques are discussed in Section 5.

Parameters to be Discussed

The important device parameters discussed in this document are summarized for bipolar transistors and diodes in Table 6.2 and for field-effect devices in Table 6.3. Readily achievable measurement accuracies and the relative importance of each parameter for some device categories are also given (see also MIL-STD-750). The degree of device characterization (the number of parameters measured and the various operating points at which these parameters are measured) will, of course, depend on the data requirements for a particular application. The priorities and measurement accuracies given in Table 6.2 and 6.3 should not be taken as specific recommendations. The selection of parameters to be measured, the number of times a parameter is measured, and the accuracies required must be based upon the requirements of the experimental design and the specific circuit application of the device. Further generalization is impractical and misleading.

Transistor gain-bandwidth product, f_T, or the delay time, t_d, are usually of interest in radiation-effects studies because these parameters are useful in the prediction of gain degradation and quality-assurance applications. Thus, the measurement of f_T and t_d may be required. Several methods are available to measure these parameters, including measurement of small signal gain or phase shift as a function of frequency, bridge and delay time methods, the measurement of scattering parameters, etc. The particular method selected will depend on the ultimate application of the data, the method of data interpretation, and the characteristics of the device to be tested. For this reason, it is impractical, at this time, to determine a preferred procedure for the measurement of f_T or t_d that would satisfy the data requirements for most applications or that is most useful in radiation-effects studies. The measurement procedure should be dictated by the intended application or the specific requirements of the experimental data. In this regard, the National Bureau of Standards is presently conducting a study of the various methods of measuring f_T and t_d to determine their limitations and advantages. The reader is referred to the NBS publications for details. In addition, numerous articles and papers are available in the literature that describe f_T and t_d measurement procedures.

Other device parameters that are usually included in electrical specifications are not included in Tables 6.2 and 6.3 because, for most devices, changes in these parameters are seldom significant at radiation levels of interest [$\sim 10^{14}$ n/cm^2 (E > 10 keV, fission) and 10^6 rads (Si)]. These parameters include, for example, the breakdown voltages and junction capacitances of transistors and diodes. In addition, a number of fundamental parameters are of interest for obtaining accurate transistor models for computer simulation of electronic-circuit behavior, including h_{FEI}, T_{CN}, and T_{CI} in the

TABLE 6.2. BIPOLAR-TRANSISTOR AND DIODE PARAMETER REQUIREMENTS – PERMANENT DEGRADATION

Device Category	Important Parameters and Readily Achievable Measurement Accuracy[a]								
	h_{FE} h_{fe} ±5%	$V_{CE(sat)}$ $V_{BE(sat)}$ ±5%	I_{CBO} I_{EBO} ±5%[b]	V_{BE} ±2%	t_r t_s t_f ±10%[c]	V_F ±5%	I_R ±5%	t_{rr} ±10%	V_Z ±0.1%
Power transistors	(1)	(2)	(3)	(4)					
Switching transistors	(1)	(2)	(4)	(5)	(3)				
Linear transistors	(1)	(2)	(3)	(4)	(5)				
Matched-pair transistors	(2)	(4)	(3)	(1)					
Switching diodes and rectifiers						(1)	(2)	(3)	
Reference diodes						(2)			(1)

(a) Numbers in parentheses indicate relative parameter priority.
(b) Function of the magnitude of the currents.
(c) Readily achievable measurement precision.

TABLE 6.3. FIELD-EFFECT-TRANSISTOR PARAMETER REQUIREMENTS – PERMAMENT DEGRADATION

Device Category	Important Parameters and Readily Achievable Measurement Accuracy[a]				
	g_m ±5%	I_{DSS} $I_{DS(ON)}$ ±5%	V_T ±5%	I_{GSS} $I_{DS(OFF)}$ ±10%[b]	$V_{DS(ON)}$ ±5%
JFET					
Amplifier	(1)	(2)	(3)	(4)	(3)
Analog switch	(5)	(1)	(2)	(4)	(3)
MOSFET					
Digital switch	(5)	(2)	(1)	(4)	(3)
Analog	(2)	(3)	(1)	(4)	(5)

(a) Numbers in parentheses indicate relative parameter priority.
(b) Function of the magnitude of the currents.

single-pole charge-control model. In some cases, measurement of these parameters that serve to characterize the device electrically are part of measurements made in the course of a radiation experiment. Specific procedures for making electrical measurements of parameters not listed in Tables 6.2 and 6.3 can be found in MIL-STD-750 and in numerous papers in the literature.

Specific Test Procedures

Specific recommended test procedures for measurement of the parameters given in Table 6.2 and 6.3 for bipolar transistors, field-effect transistors, semiconductor diodes, and Zener diodes are described below. When planning for a test at a radiation facility, several basic considerations and test-design decisions, which are not related to the measurement of a particular parameter, must be made. A discussion of these general test considerations is given in Section 2.5.

Specific test procedures are presented for "pre/post" tests (test where parameter measurements are made before and after the sample is exposed to radiation). No distinction will be made between pre/post tests and pre/post series of tests. In addition, specific procedures are given for "in situ tests" (tests in which the experimental samples are instrumented at the radiation facility so that parameter measurements can be made during the radiation exposure without removing the samples from their irradiation position). In some cases, procedures for in situ tests are not given, either because such tests are usually not performed or because a specific measurement procedure has not yet been proven. In general, the choice of pre/post test or in situ test for permanent-damage characterization of semiconductor devices is optional in most cases. Examples in which in situ tests are required include measurements of transient annealing after a neutron pulse and measurements on semiconductor devices associated with surface effects.

Data which should be taken and which are common to all tests are enumerated here and will not be repeated in the descriptions of specific test procedures. It is recommended that the following data be recorded in the course of a pre/post test or pre/post series of tests:

(1) Neutron fluence, neutron spectrum, and gamma dose (or gamma dose rate) in the locale of each group of samples for each irradiation

(2) The irradiation time period and the time period between irradiation and measurement

(3) Ambient temperature during irradiation and measurement

(4) The accuracy and precision of the measurement expected.

In addition to the above data, the following should be recorded in the course of an in situ test:

(a) Time history of the irradiation rates

(b) Time history of irradiation-chamber temperature.

Additional information on the requirements for data reporting is given in Section 6.3.

Procedures are presented for the basic methods of making parametric measurements: the steady-state method and the pulsed method. The most common and simplest technique is to apply steady-state sources (either dc or ac) to the test circuit and observe the desired response while varying one or more of the sources in discrete steps. As power dissipation increases, the junction temperatures increase rather dramatically, altering many of the parameters of the device. The pulsed method of parameter measurement minimizes changes in junction temperature and may also be used to simulate actual operating conditions for a particular circuit design. A simple and relatively fast method of obtaining many (but not all) parameters at many operating points is to use a curve tracer to sweep out a family of device characteristics and display them on an oscilloscope. Both steady-state and pulsed measurements can be made by this method. This method typically yields data with an uncertainty of at least 5 percent, so it is not recommended for critical design-data purposes.

Of the basic methods of making parametric measurements – steady-state or pulsed – one may be omitted from the preferred procedure dealing with a specific parameter measurement, either because it does not apply or because the extension to that method is obvious. Curve-tracer methods of making measurements are indicated in the applicable cases.

The choice of a particular measurement method must involve consideration of the ultimate circuit application of the device (if known), accuracy requirements, cost limitations, the number of measurements to be made, and methods of data reduction. Regardless of the particular method(s) chosen, conditions should be identical for preirradiation and postirradiation measurements, as far as possible. In case a large number of measurements are planned, consideration should be given to automating the measurements and the data reduction procedure. Although such methods are not described here, the suggested measurement circuitry can be modified to allow for automated measurement schemes and machine-oriented data reduction.

The techniques that follow should be considered as those that are preferred and recommended. The circuit configurations, however, should

be regarded only as suggested or exemplary setups. The latter have found wide acceptance but are certainly not unique, since many variations are allowable without sacrificing the ultimate worth of the data obtained. All circuit configurations are given for NPN transistors and N-channel FETs. Changes which must be made for application to PNP transistors and P-channel FETs should be obvious.

Certain portions of the exemplary circuit configurations are assumed to be isolated from the radiation environment. Such isolation is either indicated by cabling (for in situ tests) or is simply understood (for pre/post tests). Care should be taken to assure the existence of that isolation.

Transistor Current Gain, h_{FE}

h_{FE} is the large-signal, common-emitter, static forward current-transfer ratio of a transistor, also called the common emitter, d-c current gain:

$$h_{FE} \equiv \frac{I_C - I_{CBO}}{I_B + I_{CBO}} \quad .$$

The quantity I_{CBO} is the collector-base cutoff current. Usually, the cutoff current is negligible compared with the base and collector currents ($h_{FE} = I_C/I_B$); thus the requirement for determining h_{FE} is an accurate measurement of the base and collector currents at a given temperature and operating point.

h_{FE} is a strong function of current level. The rate of degradation of h_{FE} is also current dependent. Therefore, unless specific requirements dictate otherwise, it is suggested that all h_{FE} measurements be made with the emitter current or the collector current maintained constant. This is normally most convenient for design and instrumentation purposes. Measurements at constant emitter current are often desirable when the experimentalist wishes to relate results directly to injection level. Also, to be meaningful, h_{FE} should be measured only when the transistor is operating in the normal active region (the emitter-base voltage greater than or equal to zero and the collector-base voltage less than or equal to zero). It should be noted that the saturation-active-region boundary may be difficult to identify for high-voltage transistors, especially after neutron irradiation. h_{FE} depends on V_{CE}, especially at operating points near the saturation region and at high current levels. If possible, for each of several values of V_{CE}, h_{FE} data should be taken at as many bias levels as are sufficient to construct h_{FE} versus I_E or I_C curves over the full operating range of the device. For measurements near the saturation region, it should be noted that since the saturation voltage increases with neutron fluence, it may not be possible after irradiation to attain the pretest operating point. In addition, with I_C or I_E held constant, the V_{CE} for active operation increases approximately

exponentially with neutron fluence such that h_{FE} measurements may be made in active and partial saturation in the same test, which greatly complicates the h_{FE} degradation model.

The values of h_{FE} after neutron irradiation will be lower than the preirradiation value; therefore, with I_E or I_C constant, the postirradiation base current for a given operating point will be larger than the preirradiation base current. If the postirradiation h_{FE} is very low, care should be taken not to exceed the base-emitter dissipation rating when attempting to achieve the preirradiation operating point.

Pre/Post Measurements. Using a curve tracer, h_{FE} is calculated using data points obtained from the displayed family of collector characteristics (I_C versus V_{CE} for various I_B). The relative inaccuracy of this method should be considered in the light of data requirements. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- Curve-tracer front-panel settings
- Photographs of the collector characteristics
- Ambient temperature.

An arrangement for making steady-state h_{FE} measurements is shown in Figure 6.1.

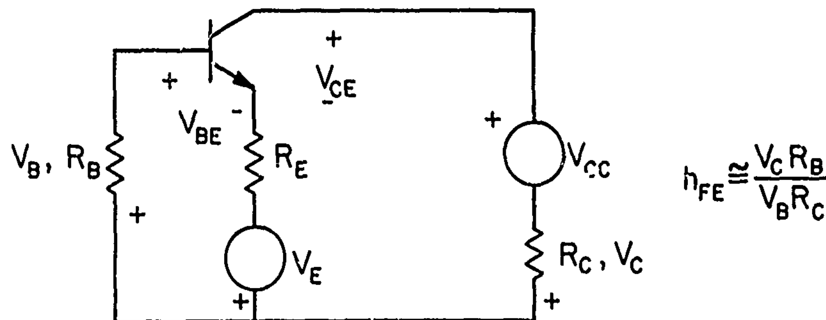


FIGURE 6.1. PRE/POST, STEADY-STATE h_{FE} MEASUREMENT CIRCUIT

The circuit components in Figure 6.1 are defined as follows:

- V_E – An adjustable voltage source used to set I_E ($V_E >> V_B$ and V_{BE}, for constant emitter current bias – usually $V_E > 10$ volts)

- V_{CC} – An adjustable voltage source used to set V_{CE}
- R_E – A resistor chosen to provide proper emitter current range
- R_B – A sampling resistor that provides a sensitive indication of I_B
- R_C – A sampling resistor that provides a sensitive indication of I_C ($V_C << V_{CC}$ for constant collector-emitter voltage).

V_E, R_E, and V_{CC} are adjusted until the required operating point is achieved. The circuit in Figure 6.1 will provide constant emitter current bias for all practical test conditions provided V_E greater than approximately 10 volts is applied. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_E, V_{CC}
- R_E, R_B, R_C
- V_B, V_C, V_{CE}
- Ambient temperature.

An alternative arrangement for making steady-state h_{FE} measurements is shown in Figure 6.2. Operational amplifiers are used in closed loops to set a constant collector current and to sense base current. Since the constant collector-current supply automatically sets the selected operating point, the measurement can be made quite rapidly. This permits momentary application of the bias, thereby reducing junction heating.

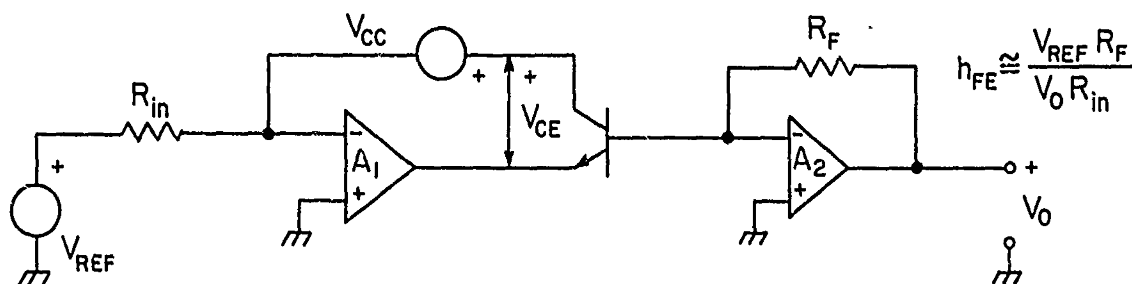


FIGURE 6.2. PRE/POST, STEADY-STATE h_{FE} MEASUREMENT CIRCUIT

The circuit components in Figure 6.2 are defined as follows:

- A_1 - An operational amplifier capable of accepting maximum emitter current
- A_2 - An operational amplifier capable of supplying maximum base current
- V_{REF} - A high-stability, adjustable power supply with fine resolution, capable of supplying maximum collector current
- V_{CC} - An adjustable voltage source used to set V_{CE}
- R_{in} - A stable precision resistor capable of providing all necessary values of I_C
- R_F - A stable precision resistor ($R_F I_B$ must be less than the saturation voltage of A_2).

Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- R_{in}, R_F
- V_{REF}, V_{CC}, V_0, V_{CE}
- Ambient temperature.

A pulsed method of measuring h_{FE} is illustrated in Figure 6.3.

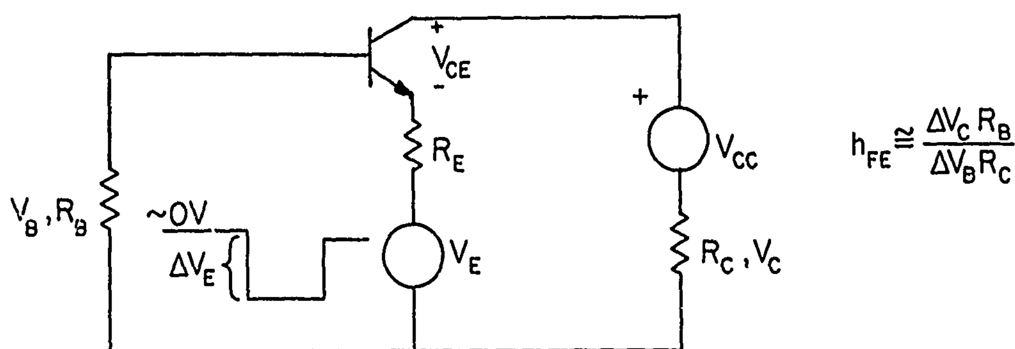


FIGURE 6.3. PRE/POST, PULSED h_{FE} MEASUREMENT CIRCUIT

The circuit components in Figure 6.3 are defined as follows:

- V_E - A pulsed voltage source with zero bias level
- V_{CC} - An adjustable voltage source
- R_E - A noninductive resistor chosen to provide the proper emitter current range
- R_B - A noninductive precision sampling resistor that provides a sensitive and convenient indication of I_B ($\Delta V_B << \Delta V_E$)
- R_C - A noninductive precision sampling resistor that provides a sensitive and convenient indication of I_C (values of R_C should be chosen to effect a constant V_{CE}).

ΔV_E, R_E, and V_{CC} are adjusted until the required operating point (I_C and V_{CE}) is achieved. The amplitude of V_B and V_C is measured with an oscilloscope with a voltage comparator preamplifier. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_{CC}, V_E, V_{CE}, V_B, V_C
- R_E, R_B, R_C
- Pulse width and duty cycle
- Ambient temperature.

The input-pulse width should be large enough to achieve steady-state or application conditions. Care should be exercised to prevent pulsing the transistor into saturation. The circuit in Figure 6.2 can also be adapted for pulsed measurements by interchanging V_{REF} with a suitable pulse generator.

Transistors designed for high-frequency operation sometimes have a tendency to oscillate. Provisions for detecting oscillations should be part of the test procedure (see Section 2.5 for some suggested methods to eliminate oscillations of the test circuit).

In Situ Measurements. The curve tracer is not generally recommended for application in in situ measurements because capacitance introduced by the long leads may affect the response of the instrument.

The steady-state and pulsed methods are applicable to in situ measurements when modified to include the required cables between the instrumentation and the test sample. In pulsed in situ tests, care should be taken to insure proper termination of all cables.

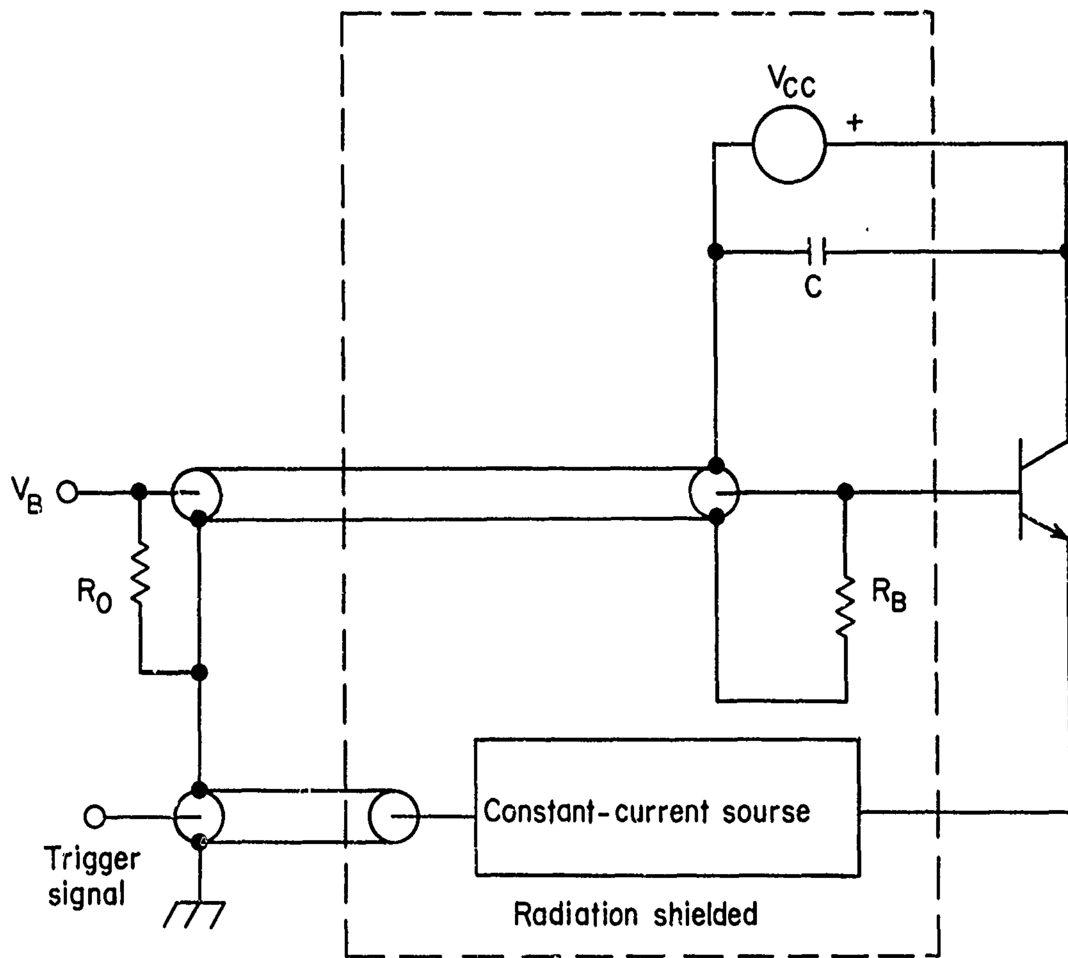
An arrangement for making rapid annealing measurements of h_{FE} is shown in Figure 6.4. The circuit utilizes a constant current source to maintain the proper emitter current during measurement. The circuit provides a means (using a proper trigger signal) of maintaining the transistor under test in the cutoff condition (minimum injection condition) during portions of the experimental period. Note that annealing is minimized while the transistor is cut off. The operating condition of the transistor during and immediately following irradiation will, of course, be determined by the requirements on the data and the experimental design.

The Figure 6.4 circuit components are defined as follows:

- Constant-current source – Selected to provide constant emitter current for all expected values of transistor gain
- V_{CC} – A battery to set collector voltage
- R_O – Cable characteristic resistance
- R_B – May be added to reduce the total base voltage drop
- C – Collector bypass capacitor.

The emitter current, I_E and V_{CC} must be selected so that the required transistor operating point is achieved. The voltage V_B is monitored on an oscilloscope to provide an indication of the base current. The direct measurement of the collector current is generally not required when a constant emitter current source is used. The bypass capacitor is used to provide a stiff collector voltage and minimize oscillations (the large value bypass capacitor should be shunted by a small value low-inductance disc capacitor). The proper signals to trigger the current source and the oscilloscopes are implicit in Figure 6.4 and must be supplied. A useful reference for timing is the incidence of the neutron pulse. A preburst and postburst sweep are required to establish initial and final h_{FE} values and reveal any scope drift problems that could compromise calibration. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_{CC}, I_E
- R_O, R_B
- V_B



$$h_{FE} \approx \frac{I_E R_O R_B}{V_B(R_O + R_B)} - 1$$

FIGURE 6.4. RAPID-ANNEALING h_{FE} MEASUREMENT CIRCUIT

- Oscilloscope time scales including the delay between neutron pulse and scope triggering
- Time delay between neutron pulse and triggering of the current source
- Ambient temperature of samples
- Gamma dose rate.

Transient-annealing measurements are complicated by variations of the ambient temperature and by the photocurrents generated by the gamma radiation accompanying a neutron pulse. For meaningful data analysis, the temperature and the gamma dose rate must be monitored during a rapid-annealing experiment. Note that from 1 to 10 percent of the maximum gamma dose rate can persist for milliseconds after the neutron pulse. For this reason, extreme care should be exercised in analyzing rapid-annealing data.

Transistor Small-Signal Current Gain, h_{fe}

h_{fe} is the small-signal, short-circuit, forward current-transfer ratio of a transistor ($h_{fe} = \partial I_C/\partial I_B \mid V_{CE}$) operating in the normal active region, also known as ac beta. The requirement for determining h_{fe} is an accurate measurement of a small change in collector current for a given small change in base current at a given temperature and operating point.

All preliminary comments found in the preceding subsection on the measurements of h_{FE} apply here as well.

Pre/Post Measurements. A steady-state technique that employs sinusoidal excitation is shown in Figure 6.5.

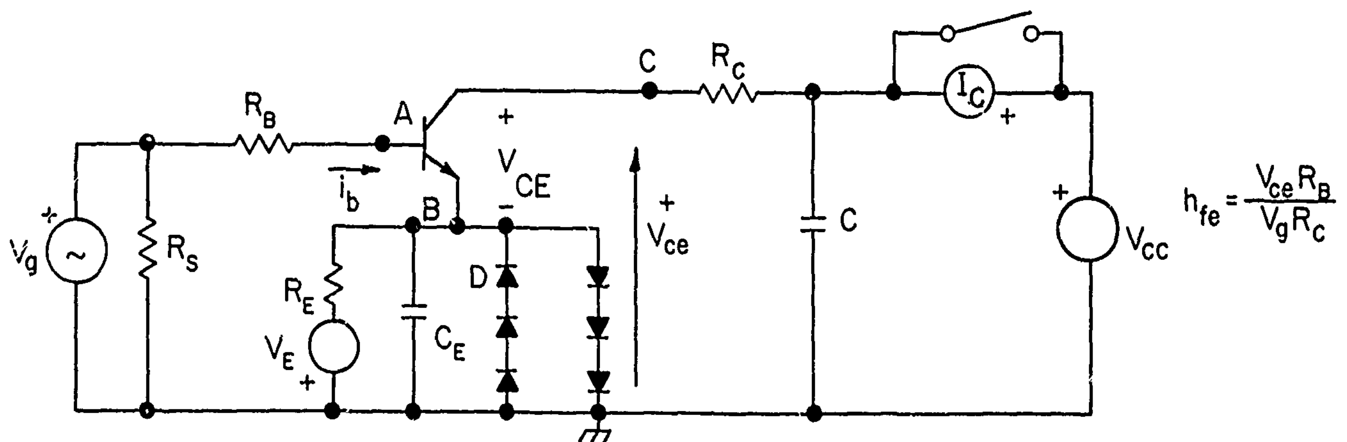


FIGURE 6.5. PRE/POST, STEADY-STATE h_{fe} MEASUREMENT CIRCUIT

The circuit components in Figure 6.5 are defined as follows:

- I_C – A meter to establish the dc collector current. Once I_C is established the meter is shorted.
- R_B – A precision resistor large enough to insure that $i_b = V_g/R_B$
- R_E – A resistor used to set emitter current range
- R_C – A resistor chosen as small as possible while still maintaining usable sensitivity
- R_S – Signal-generator termination
- C_E – Emitter bypass capacitor at test frequency
- C – Power supply bypass capacitor at test frequency
- D – Diodes used to protect transistor sample from burnout when interchanging samples
- V_E – An adjustable voltage source to set emitter current
- V_{CC} – An adjustable voltage source
- V_g – A sinusoidal-signal generator at the test frequency (typically 1 k Hz)
- Points A, B, and C are used for <u>in situ</u> measurements (described next).

The operating point is set by adjusting V_E and V_{CC}. To hold V_{CE} nearly constant, V_{ce} should be as small as can be accurately measured. Measured values of V_{ce} and V_g may be either peak or rms. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- R_B, R_C, R_E, R_S
- C_E, C
- V_E, V_{CC}, V_{CE}, I_C
- V_g, V_{ce}

- Test frequency

- Ambient temperature.

The circuit of Figure 6.5 is usable for frequencies up to approximately 25 MHz if the following precautions are taken during construction of the circuit:

(1) The generator and its signal cable must be properly terminated.

(2) All lead lengths must be kept to a minimum.

(3) The components must have suitable characteristics at the test frequency.

(4) The base and collector circuits must be shielded from each other and from extraneous RF interference.

Pulsed h_{fe} measurements are usually not required in radiation-effects work, and thus no specific recommendations will be made.

In Situ Measurements. The procedure for pre/post, steady-state h_{fe} measurement, as illustrated in Figure 6.5, applies also to *in situ* measurements. Three cables (shielded or coaxial, inserted at Points A, B, C in Figure 6.5) should be run from the irradiation chamber. All cables should possess a common-ground connection. The frequency used for *in situ* test should be limited by consideration of cable effects at the higher frequencies.

Transistor Saturation Voltages, $V_{CE(sat)}$ and $V_{BE(sat)}$

$V_{CE(sat)}$ is the dc voltage between collector and emitter of a transistor operating in a specified condition of saturation; $V_{BE(sat)}$ is the dc base-emitter voltage in that condition.

The requirement for determining $V_{CE(sat)}$ is an accurate measurement of the collector-to-emitter voltage of a saturated transistor at a specified base current and collector current. $V_{BE(sat)}$ is the base-to-emitter voltage under the same conditions. All measurements should be confined to the saturation region (both junctions forward biased). In addition, measurement of $V_{CE(sat)}$ and $V_{BE(sat)}$ should be made at identical operating points. Care should be taken to isolate cable-, lead- and contact-voltage drops from the measurements of $V_{CE(sat)}$ and $V_{BE(sat)}$, especially at high currents.

Samples should be measured at the value of forced gain, I_C/I_B, of interest. If no particular operating point is important, it is convenient to measure $V_{CE(sat)}$ and $V_{BE(sat)}$ as functions of I_B for various values of I_C. Separate measurements should generally be made at operating points that differ by more than a factor of 2 in collector current.

Pre/Post Measurements. $V_{CE(sat)}$ at the specified base and collector currents is directly obtained from the display of collector characteristics on a curve tracer. $V_{BE(sat)}$ at the same operating conditions as $V_{CE(sat)}$ is directly obtained from a display of V_{BE} as a function of V_{CE}; this is not a common display. This display is obtained by first displaying the family of collector characteristics and then changing the vertical display to monitor base-emitter voltage. V_{BE} versus V_{CE} is a family of characteristics having one curve for each base current step.

Steady-state measurements may be made using the same configurations as shown in Figures 6.1 and 6.2, except that the operating points are chosen in saturation. In Figure 6.2, the output voltage of A_1 must be monitored to obtain V_{BE}. When measuring power devices, values of forced gain (I_C/I_B) chosen should be small to assure that preirradiation operating points can be attained after gain degradation. Care must be taken during steady-state measurements to limit device dissipation in order to avoid excessive temperature buildup and the associated change in device characteristics.

Pulsed measurements may be made using the same configuration as shown in Figure 6.3, except that the operating points are chosen in saturation. Pulsed techniques are preferred since device heating is minimized.

In Situ Measurements. The steady-state and pulsed methods for pre/post measurements are applicable to in situ measurements of $V_{CE(sat)}$ and $V_{BE(sat)}$ when modified to include the required cables between the instrumentation and the sample.

Transistor Base-Emitter Voltage, V_{BE}

The requirement for determining V_{BE} is an accurate measurement of base-emitter voltage as a function of collector current for various values of V_{CE}. The measurements should be confined to the normal active region.

V_{BE} measurement assumes importance for the case of matched-pair devices operated in the normal active region as a differential amplifier. For this mode of operation, the curves of I_C versus V_{BE} are matched.

It is necessary to measure the I_C versus V_{BE} dependences of both devices of a matched-pair at collector currents extending from low currents (~10 μA) to currents somewhat larger (~30 percent) than that at which h_{FE}

is a maximum. The number of current levels at which these measurements should be made is a function of the useful current range of the particular device type. However, it is not necessary to take data at successive current levels which are closer than one-third decade. The optimum technique for measurements on matched-pair devices is to monitor directly the differential base-emitter voltage as a function of neutron fluence.

Either steady-state or pulsed methods may be employed to measure these characteristics. The curve tracer may be an X-Y recorder. If so, the input should be a fast, single-sweep ramp voltage that is compatible with recording speed. The circuitry of Figures 6.1 and 6.2 can be adapted to any of these measurement techniques if provisions are made to monitor V_{BE}. The adapted circuits then may be modified for differential measurements.

The impedance of the base-emitter junction is a function of the operating point. The impedance of the instrument used to indicate the junction voltage must not perturb the circuit at low input currents.

Since the I_C-V_{BE} characteristic is quite temperature sensitive, the sample temperature should be recorded and maintained constant during measurement. This can be accomplished by using a heat sink and avoiding slow ramp voltages or high duty cycle. Significant changes in these characteristics can result from simply handling the sample.

To facilitate comparisons, it is normally desirable to plot the pretest and posttest curves for a given sample on the same sheet of paper if an X-Y recorder is used.

In situ measurements may be performed by simply modifying the circuit configurations for steady-state and X-Y recorder measurements to include the required cables between the device and the instrumentation.

Diode Forward Voltage, V_F

V_F is the voltage across a diode under conditions of forward bias. The information normally required is a curve of V_F versus I_F, the forward current. Diode forward-voltage drop should be measured at several current levels (at least every half decade) over the operating range of the device (3 to 5 decades).

The measurement techniques and precautions that must be taken are very similar to those for transistor base-emitter voltage, V_{BE} (preceding subsection). The basic circuit configuration is shown in Figure 6.6.

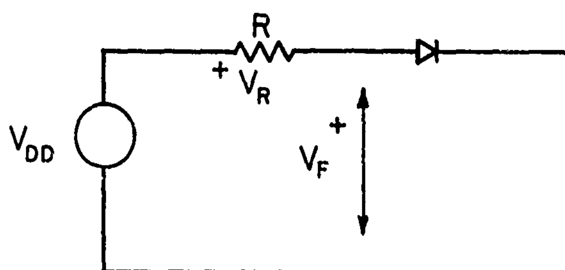


FIGURE 6.6. BASIC V_F MEASUREMENT CIRCUIT

The circuit components in Figure 6.6 are defined as follows:

- V_{DD} – An adjustable voltage source
- R – A precision sampling resistor that provides a sensitive and convenient indication of I_F.

Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_{DD}
- R
- V_F, V_R
- Ambient temperature.

This technique is applicable to both conventional diodes and Zener diodes.

Diode Zener Voltage, V_Z

V_Z is the Zener breakdown voltage of a diode. The information required is the value of V_Z at a particular current I_Z, which is a function of the device application. The measurement of V_Z should be made at a constant current level and constant temperature at the specific operating point dictated by the application requirements. If the operating point is not specified, V_Z should be measured at several current levels from low currents to the maximum safe reverse current. In addition measurements can also be made at several temperatures to provide a measure of the effect of radiation on the temperature coefficient. The most stringent requirement of the measurement technique is that the accuracy of the measurement must be within 0.1 percent because observed variations in V_Z are usually rather small. Also, some devices have

rather large temperature coefficients of Zener voltage; hence, temperature control is usually required.

The basic measurement technique requires accurate current-voltage characteristics of the device. Steady-state measurements should be made using a precision voltmeter and a precision sampling resistor (current measurement) similar to the circuit shown in Figure 6.6 where the supply polarity is reversed to obtain the reverse I-V characteristic of the diode. In some applications an active constant current generator can be used to hold errors resulting from variations in I_Z to a negligible level. To be sure that changes in ambient temperature do not influence the measurement accuracy of radiation induced changes in V_Z, ambient temperature control is normally recommended especially when precision voltage references are characterized. Temperature control can be provided either by an air bath oven or a temperature controlled oil bath. Temperature control is especially important when making in-situ measurements to minimize errors from ambient temperature variations at the test facility.

A pulsed method of measuring V_Z is illustrated in Figure 6.7. The circuit components in the figure are defined as follows:

- V_2 – Adjustable precision voltage supply (0.05 percent)
- V_1 – A pulsed voltage source with zero dc level
- R – A precision resistor to set the required current range
- C – Capacitors to bypass voltage source and ac couple to oscilloscope.

V_2 is adjusted to approximately 0.99 V_Z such that no significant conduction occurs when V_1 voltage is zero. ΔV_1 is adjusted for the proper operating point (I_Z). ΔV is measured on a standard oscilloscpe. Data to be recorded include the following:

- ΔV_1, V_2
- R
- ΔV
- Ambient temperature.

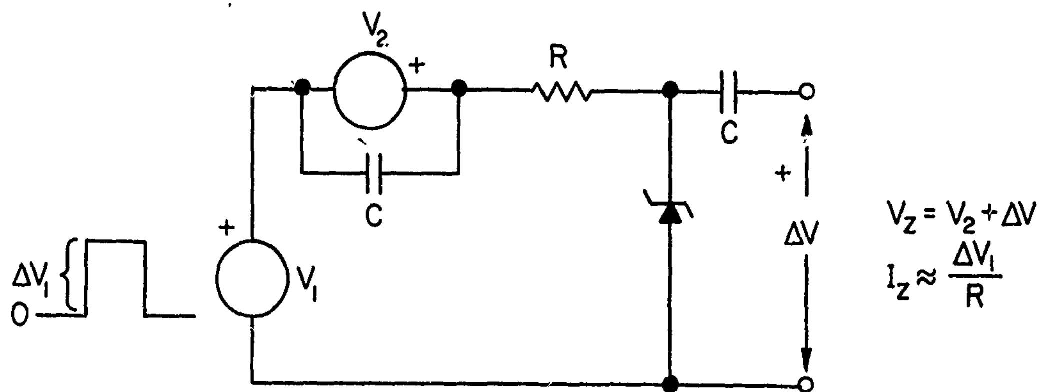


FIGURE 6.7. PULSED V_Z MEASUREMENT CIRCUIT

The above measurement procedure should be used for Zener diodes with V_Z greater than about 7 volts. For devices with $V_Z < 7$ V, the steady-state method should be used. The above procedure can be applied for in situ (rapid annealing) tests provided properly terminated cables are used between the sample and the instrumentation.

Transistor Leakage Currents, I_{CBO} and I_{EBO}

I_{CBO} is the reverse leakage current of a transistor collector-base junction when the emitter is unconnected. I_{EBO} is the reverse leakage current of a transistor emitter-base junction when the collector is unconnected.

The requirements for determining I_{CBO} and I_{EBO} are accurate measurements of leakage currents as functions of reverse-bias voltages. Since both leakage currents are functions of bias voltage, measurements at two or three operating points are usually adequate (one measurement should be at a bias voltage which is a large fraction of the junction breakdown voltage). The reverse bias must be less than the appropriate junction breakdown voltage to prevent damage to the transistor.

Pre/Post Measurements. A steady-state measurement of I_{CBO} is illustrated in Figure 6.8. I_{EBO} is measured by interchanging the collector and emitter connections.

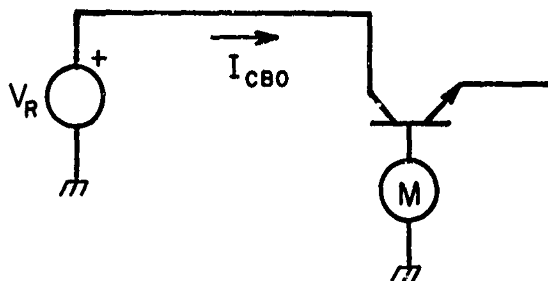


FIGURE 6.8. PRE/POST, STEADY-STATE I_{CBO} MEASUREMENT CIRCUIT

The circuit components in Figure 6.8 are defined as follows:

- V_R – An adjustable dc voltage source ($V_R < BV_{CBO}$)
- M – An instrument capable of accurate current measurement down to picoamperes.

Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_R
- I_{CBO}
- Ambient temperature.

The currents to be measured are normally extremely small; therefore, extreme caution must be exercised when making these measurements. Problems may be encountered owing to stray leakage currents and fields. It is recommended that the pretest and posttest measurements be made in a test fixture having shielded wiring that is well insulated from ground. Considerable changes in I_{CBO} and I_{EBO}, due to their temperature sensitivity, can result from simply handling the sample.

In Situ Measurements. An extension of the steady-state technique of Figure 6.8 to in situ measurements is shown in Figure 6.9. I_{EBO} is measured by interchanging the collector and emitter connections. The circuit components and recorded data are the same as for a pre/post test.

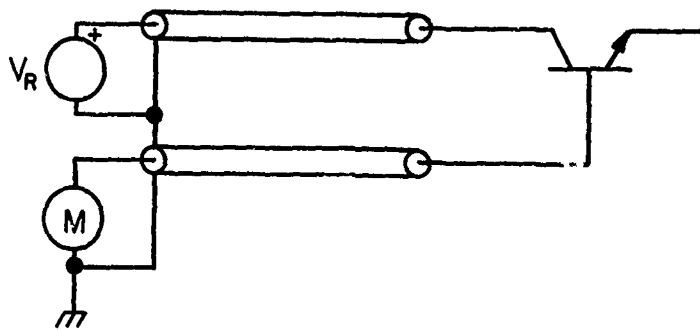


FIGURE 6.9. IN SITU STEADY-STATE I_{CBO} MEASUREMENT CIRCUIT

In addition to the recommendations and precautions given for pre/post irradiation measurements, the following should be considered. Determine the leakage current in the measurement circuit by including a measurement without a sample attached. This current must be subtracted from the currents recorded during I_{CBO} and I_{EBO} measurements. This technique is subject to some uncertainty. The degree of uncertainty can be reduced by assuring that the cables are of the same type, from the same manufacturer, if possible from the same lot, and with the same radiation history.

Diode Leakage Current, I_R

I_R is the leakage current that flows when a diode is reverse biased. The requirement for determining I_R is an accurate measurement of leakage current as a function of reverse-bias voltage.

The considerations, procedures, and precautions of measurement of I_R are identical to those of measurements of I_{CBO} and I_{EBO} given in the preceding subsection.

Transistor Switching Times, t_r, t_s, and t_f

t_r, t_s, and t_f are the rise time, storage time, and fall time, respectively, of the collector-current pulse as measured when the transistor is driven into saturation and returned to the cutoff mode. These three switching times are precisely defined in the literature and are functions of the test-circuit elements as well as normal and inverted dc current gains and cutoff frequencies. Hence, any specification of measurement technique involves specifying circuit component values as well as collector, turn-on base, and turn-off base currents. Because of the wide range of device types suitable for switching applications, it is impractical to determine a preferred procedure that would satisfy manufacturers as well as users. The measurement procedure should be dictated by the intended device application or the specific requirements of the experimental data (see also MIL-STD-750). When making

measurements of the switching characteristic of transistors, the experimentalist should carefully review the limitations and accuracy of the particular measurement scheme and the specific test equipment used.

Diode Reverse-Recovery Time, t_{rr}

t_{rr} is the reverse-recovery time of a diode, as defined in Figure 6.10.

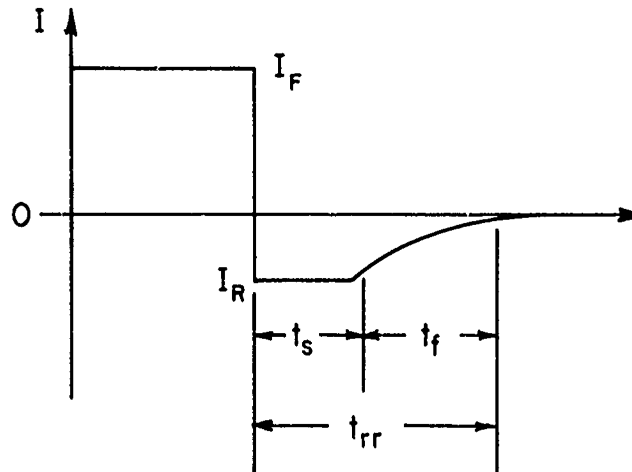


FIGURE 6.10. DIODE REVERSE-RECOVERY CHARACTERISTICS

The recovery time, t_f, may be circuit dependent, being limited by the series resistance and capacitance in the circuit. Because of this, t_s is the important switching parameter to measure. However, to give designers an estimation of the total reverse-recovery time for different circuits, it is recommended that both t_s and t_f be recorded, along with the values of I_F and I_R. The diode switching characteristic may be measured using a standard circuit such as the one in Figure 6.11. V_{DD} is an adjustable dc voltage source. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_{DD}, R
- I_F, I_R
- t_s, t_f
- Ambient temperature.

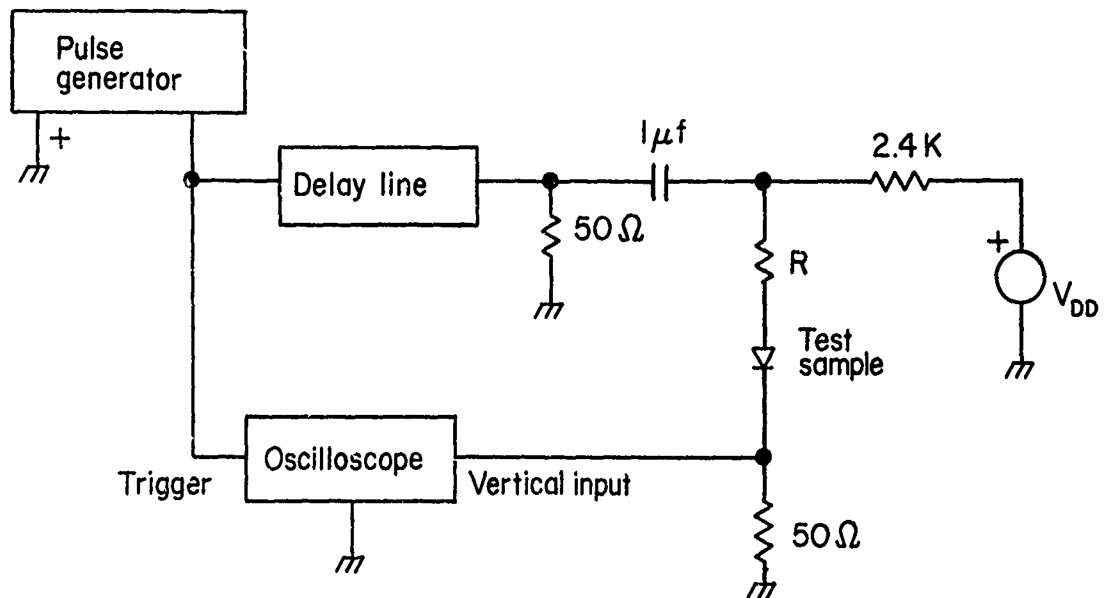


FIGURE 6.11. BASIC t_{rr} MEASUREMENT CIRCUIT

The diode is initially biased in the forward direction by V_{DD} and is turned off by a negative pulse from the pulse generator. The advantages of this measurement circuit are:

(1) The pulse generator is always properly terminated.

(2) The diode may be turned on for a time long compared with the diode response times, thus eliminating effects of pulse width on switching times. However, I_F must be low enough to minimize heating effects.

(3) Measurements may be easily made over a range of I_F/I_R for a given value of I_F.

In many cases the delay line will be incorporated in the pulse generator or in the oscilloscope. The rise times of the pulse generator and the oscilloscope must be small compared with the diode response times.

Since t_s is related to I_F/I_R, measurements should be made at values of I_F and I_R particularly applicable to the ultimate device application or to the individual diode type as specified by the manufacturer.

FET Drain Characteristic, I_{DSS} and $I_{DS(ON)}$

I_{DSS} is the zero-gate-voltage drain current measured above the knee of the drain current-voltage characteristic (pinch-off region) of a field-effect transistor. In JFETs (that operate only in the depletion mode), I_{DSS} is a measure of the maximum drain current at which the device can operate. For

MOSFET devices that operate in both the enhancement and enhancement-depletion modes, $I_{DS(ON)}$ is defined as the drain current (above the knee of the drain current-voltage characteristic) when the gate is biased for maximum channel conduction. The requirement for determining I_{DSS} and $I_{DS(ON)}$ is an accurate measurement of the drain current at the specified operating point and temperature. I_{DSS} is measured for devices operating in the depletion mode only (JFET). $I_{DS(ON)}$ is measured for devices that operate in the enhancement and depletion-enhancement modes (MOSFET).

Since I_{DSS} and $I_{DS(ON)}$ depend on the drain-source voltage, V_{DS}, data should be taken at operating points in the range between the pinch-off voltage, V_p, and the gate-drain breakdown voltage, BV_{DS}. Usually measurements should be made at V_{DS} near V_p, V_{DS} near BV_{DS}, and V_{DS} near $BV_{DS}/2$, unless specific requirements dictate otherwise.

Pre/Post Measurements. Using a curve tracer, I_{DSS} and $I_{DS(ON)}$ are determined from the displayed family of drain characteristics (I_D versus V_{DS} for various V_{GS}). Care should be exercised in adjusting the gate voltage steps on the curve tracer since N-channel JFETs can be destroyed by application of over 0.5-volt positive bias. Data to be recorded should include the following:

- Complete description of circuitry and equipment
- Curve tracer front-panel settings
- Photographs of drain characteristics
- Ambient temperature.

An arrangement for making steady-state I_{DSS} and $I_{DS(ON)}$ measurements is shown in Figure 6.12. The circuit components in the figure are defined as follows:

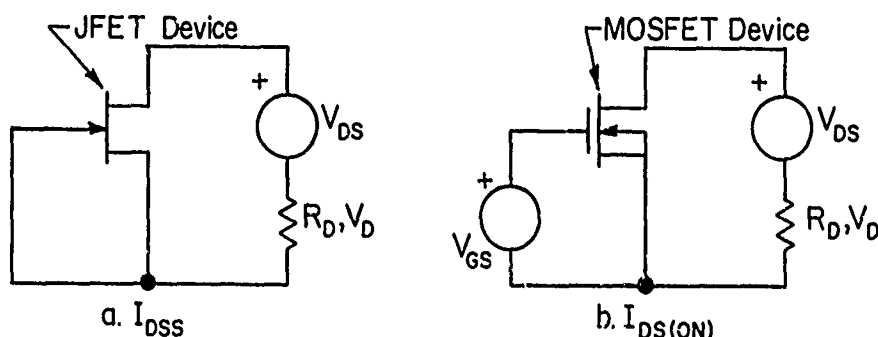


FIGURE 6.12. PRE/POST, STEADY-STATE I_{DSS} AND $I_{DS(ON)}$ MEASUREMENT CIRCUIT

- V_{DS} – An adjustable voltage source
- V_{GS} – An adjustable voltage source
- R_D – A resistor chosen to provide an indication of I_D of the proper sensitivity (R_D should be as small as possible such that $V_D \ll V_{DS}$).

V_{DS} and V_{GS} are used to set the proper operating point, i.e., for I_{DSS} measurement $V_{GS} = 0$ and for $I_{DS(ON)}$, set V_{GS} for rated maximum conduction. V_{DS} must be greater than the pinch-off voltage. Data recorded should include the following:

- Complete identification of circuitry and equipment
- V_{DS}, V_{GS}
- R_D
- V_D
- Ambient temperature.

The circuits shown in Figure 6.12 can be adapted for pulsed method of measurement by replacing the V_{DS} voltage source with a pulse generator and by monitoring the voltage across R_D on a suitable oscilloscope. Pulsed measurements are usually preferred since device heating is minimized. Pulsed measurements are sometimes mandatory since the operating points required cannot be obtained (in a steady-state measurement scheme) without exceeding the dissipation ratings of the device.

In Situ Measurements. The steady-state and pulsed methods for pre/post measurements are applicable to in situ measurements of I_{DSS} and $I_{DS(ON)}$ when modified to include the required cables between the instrumentation and the sample.

FET Threshold Voltage, V_T

The threshold, or turn-on, voltage of a field-effect transistor is defined as that value of gate voltage for which current just starts to flow between drain and source. In order to arrive at a more quantitative description of V_T, it is recommended that V_T be defined as the gate voltage at which drain-source conduction reaches 10 μA for radiation-effects experiments. This definition is useful, since the leakage currents after irradiation are usually

less than 10 μA; thus measurements of V_T at the same drain current level can be repeated before and after irradiation. Measurements of V_T should be made at drain-source voltages in the pinch-off region.

The radiation-induced change in V_T is the most important radiation-induced failure mode for MOS transistors. Changes in V_T in MOS transistors are caused primarily by ionizing radiation. For this reason, irradiation tests on MOS devices are usually conducted in an ionizing-radiation environment. In addition, the changes in V_T of MOS transistors is a strong function of gate bias applied during irradiation. Note that the radiation-induced change in V_T is negative (positive V_T shifts have been observed for some MOS devices irradiated near zero gate bias). Thus, to be meaningful, MOS transistors should be irradiated with the particular bias condition required by the application. If no specific operating point is specified, MOS devices should be irradiated at several bias conditions (both positive and negative which include typical operating conditions).

Changes in V_T for both JFET and MOSFET devices can be made with the circuit shown in Figure 6.13. V_{DS} is adjusted to provide the desired drain-source voltage ($V_{DS} > V_p$). V_{GS} is adjusted until the drain current as measured on a dc microammeter reaches 10 μA. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- V_{DS}
- I_D
- V_{GS}
- Ambient temperature.

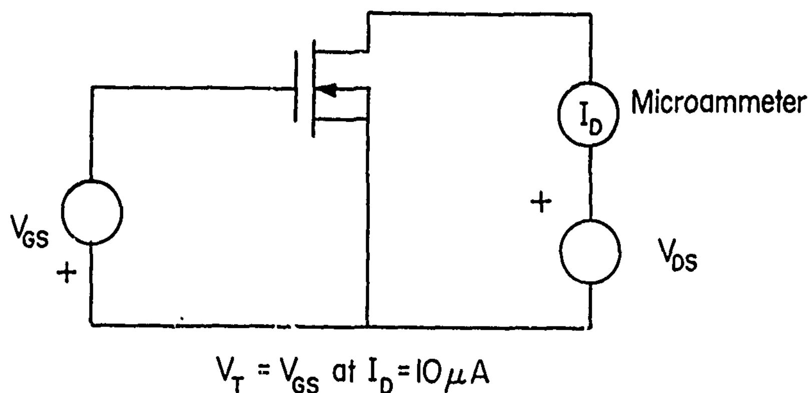


FIGURE 6.13. FET THRESHOLD-VOLTAGE MEASUREMENT CIRCUIT

Measurements can be performed either pre/post or in situ, provided the suitable cables are attached between the sample and the instrumentation for the in situ test.

FET Forward Transconductance, g_m

g_m is the small-signal, forward transconductance of a field-effect transistor defined by $g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}$. The requirement for determining g_m is an accurate measurement of a small change in drain current for a given small change in gate voltage at a given temperature and operating point. g_m can be determined from the slope of plots of I_D versus V_{GS}.

g_m is a strong function of current level due to the nonlinearity in the I_D-V_{GS} characteristics. g_m is an increasing function of drain current having its maximum value at I_{DSS} or $I_{DS(ON)}$. There is little dependence on V_{DS} provided the device is operated in the pinch-off region. If possible, for the selected values of V_{DS} (in the pinch-off region), g_m data should be taken at selected points over the full operating range of the device to construct g_m versus I_D curves. Note that irradiation decreases I_{DSS}; thus some pretest operating points may not be achieved after irradiation. Unless specific requirements dictate otherwise, it is suggested that all g_m measurements be made with V_{GS} maintained constant.

A steady-state technique for g_m measurement that employs sinusoidal excitation is shown in Figure 6. 14. The circuit components in this figure are defined as follows:

- V_{GS} – An adjustable voltage supply
- V_{DS} – An adjustable voltage supply
- I_D – A meter to establish the dc drain current (once I_D is established the meter is shorted)
- V_g – A sinusoidal voltage generator at the test frequency
- C – The bypass capacitors for the voltage sources
- R_g – The gate resistance, usually about 100 kΩ

- R_D – A resistor chosen as small as possible while still maintaining usable sensitivity (R_D must be chosen such that $R_D << r_D$, where r_D is the dynamic output resistance of the device).

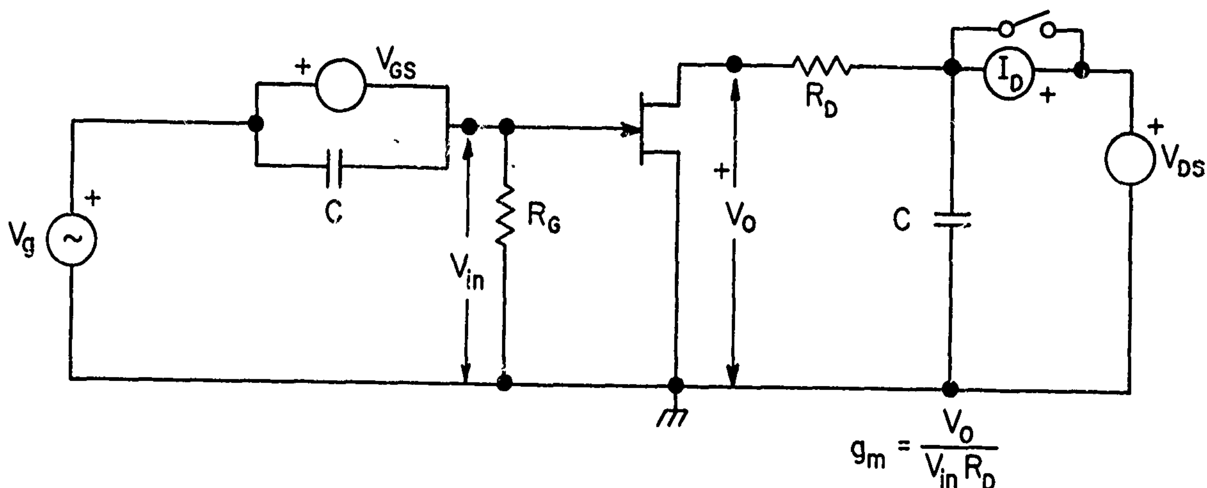


FIGURE 6.14. FET SMALL-SIGNAL-g_m MEASUREMENT CIRCUIT

The operating point is set by adjusting V_{GS} and V_{DS}. To hold V_{DS} nearly constant, V_0 should be as small as can accurately be measured. Measured values of V_{in} and V_0 may be either peak or rms. Data to be recorded should include the following:

- Complete identification of circuitry and equipment
- R_G, R_D, C
- V_{GS}, V_{DS}, I_D
- V_{in}, V_0
- Test frequency
- Ambient temperature.

Usually g_m measurements are made at 1 kHz; however, if the proper precautions are taken, the circuit in Figure 6.14 can be used up to 25 MHz (see the preceding subsection on "Transistor Small-Signal Current Gain, h_{fe}"). Either pre/post or in-place measurement can be made provided the proper cables are provided for the in situ test.

FET Leakage Currents, I_{GSS} and $I_{DS(OFF)}$

I_{GSS} is the gate leakage current of a field-effect transistor with the drain shorted to the source. $I_{DS(OFF)}$ is the drain source current with the channel off. The requirements for determining I_{GSS} and $I_{DS(OFF)}$ are similar to those discussed in the earlier subsection on the leakage currents I_{CBO} and I_{EBO} of junction transistors. Measurement arrangements are illustrated in Figure 6.15. I_{GSS} is normally measured for JFET devices while $I_{DS(OFF)}$ is measured for MOS devices. V_{GS} is used to set the required reverse bias voltage while the leakage current is measured with an instrument capable of current measurement down to picoamperes. Measurements should be made with test fixtures having shielded wiring that is well insulated from ground. The ambient temperature of the samples should be held constant.

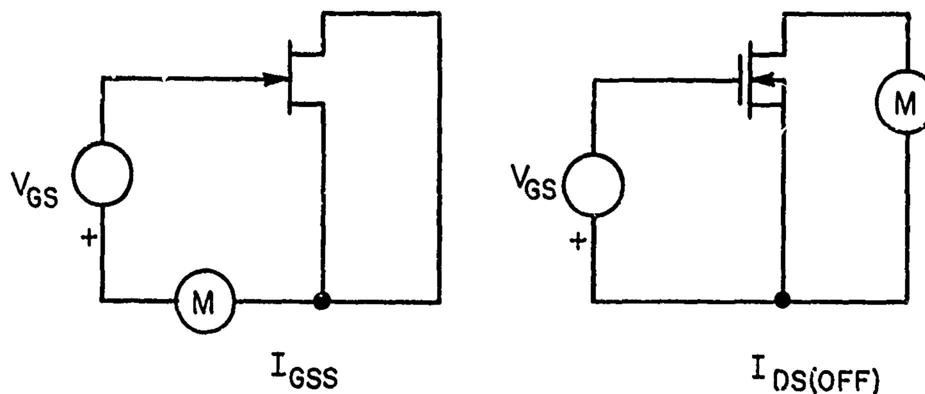


FIGURE 6.15. FET LEAKAGE-CURRENT MEASUREMENT CIRCUIT

FET Drain-Source Saturation Characteristic, $V_{DS(ON)}$

$V_{DS(ON)}$ is the dc voltage between the drain and source of an FET operating in a specified condition in the resistance region ($V_{DS} < V_p$). $V_{DS(ON)}$ describes the nonlinear voltage drop due to the resistance of the channel in series with the drain and source. This parameter is of primary

importance for switching and chopper applications. Measurements of $V_{DS(ON)}$ should be made at the particular operating point of interest. If no particular operating point is important, it is convenient to measure $V_{DS(ON)}$ as a function of V_{GS} for various values of I_D. $V_{DS(ON)}$ is directly obtainable from the display of the drain-current characteristics on a curve tracer. Steady-state and pulsed measurements may be made using the same configuration as shown in Figure 6.12, except that the operating points are chosen in the resistance region and the drain source voltage is directly measured. Care must be taken during steady-state measurements to avoid excessive temperature buildup and the associated change in device characteristics.

6.2 TRANSIENT-RESPONSE MEASUREMENTS

Scope

This section deals with experimental procedures for determining the time history of primary photocurrents (I_{pp}) generated within conventional discrete bipolar injection transistors, MOS and junction field-effect transistors, semiconductor diodes, and Zener diodes, when they are exposed to sources of ionizing radiation. Extrapolation of the procedures set forth here for application to other devices and/or other kinds of radiation should be performed with great care. The recommended procedures that follow have been found to be valid for ionizing-radiation dose rates as great as 10^{10} rads (Si or Ge)/s. The procedures may be used for measurements at dose rates as great as 10^{12} rads (Si or Ge)/s, but the uncertainties are not well known.

Analytical Techniques

This document is primarily concerned with several experimental techniques for radiation-effects work. However, the designer should be aware of theoretical and empirical techniques for predicting primary photocurrent in semiconductor devices. These analytical techniques may prove to be applicable under the following circumstances:

(1) When an estimate of I_{pp} must be made in preparation for future testing

(2) When less accurate results will suffice for design data

(3) When testing must be limited, but additional data are required.

Two empirical methods are available – the storage-time method and the avalanche method. In both approaches, nondestructively measured electrical parameters are employed to calculate probable photocurrents and radiation storage times within specified confidence limits. The reader is directed to the bibliography for further information regarding theoretical and empirical techniques.

Parameters to be Discussed

It is generally agreed that the most valuable ionization-effects data for the designer are specifications of the primary photocurrents as functions of time at various conditions of fixed-voltage bias in response to known ionizing-radiation dose-rate profiles. In diodes, a single photocurrent, designated I_{pp}, is of interest. In transistors, two photocurrents are of interest. The collector-base photocurrent is designated I_{ppc}; the emitter-base photocurrent is designated I_{ppe}. In the majority of cases, I_{ppe} is neglected because its value is small relative to the value of I_{ppc}. In some instances, the secondary photocurrent, I_{sp}, in transistors and the radiation storage time, t_{sR}, in diodes and transistors may be of interest. In field-effect transistors, the transient response includes the drain PN junction primary photocurrent, I_{ppd} (since the FET device is symmetric, a similar photocurrent, I_{pps}, is generated at the source), the channel response, and the influence of charge emission and ionization currents generated in the gate circuit on the drain current by gain action in the field-effect transistor. The procedures described here are applicable to the measurement of all these parameters. Distinctions will not be made unless required.

To illustrate the effect of ionizing radiation on semiconductor devices, a generalized PN junction will be considered as defined in Figure 6.16. The primary photocurrent (designated by the current source in Figure 6.16) flows in the direction shown and is a function of radiation dose rate ($\dot{\gamma}$) and dose (γ) in the device material, the reverse-bias voltage (V_R), and time (t). It is also a function of the type and energy spectrum of the incident ionizing radiation. In many cases, several of these dependencies will not be strong and may be neglected; however, the most general case is illustrated in Figure 6.16.

A somewhat typical primary-photocurrent response to a rectangular pulse of ionizing radiation is shown in Figure 6.17. There exists a dose dependence of I_{pp} immediately after onset of the radiation. This dependence disappears with increasing time and becomes a pure dose-rate dependence near the end of the radiation pulse, when the primary photocurrent assumes a value ΔI_R (the so-called steady-state primary photocurrent). The value of ΔI_R for a particular constant dose rate and the device relaxation time are valuable information as they aid in the extrapolation to weapon-pulse response of a particular device. For short radiation pulses, the steady-state photocurrent of a particular device may not be achieved. Under short-pulse conditions, the primary photocharge, Q_{pp}, and the device relaxation time for

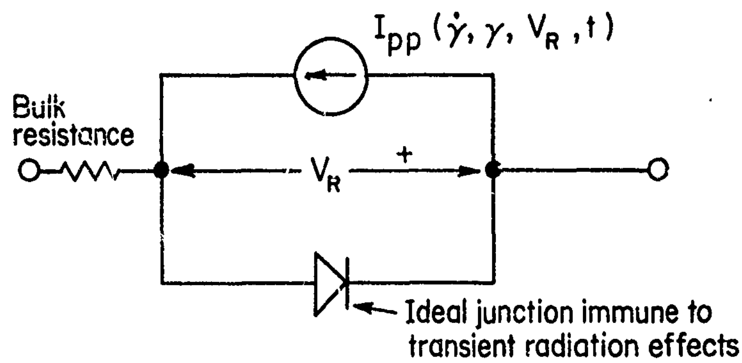


FIGURE 6.16. GENERALIZED PN-JUNCTION MODEL DURING IRRADIATION

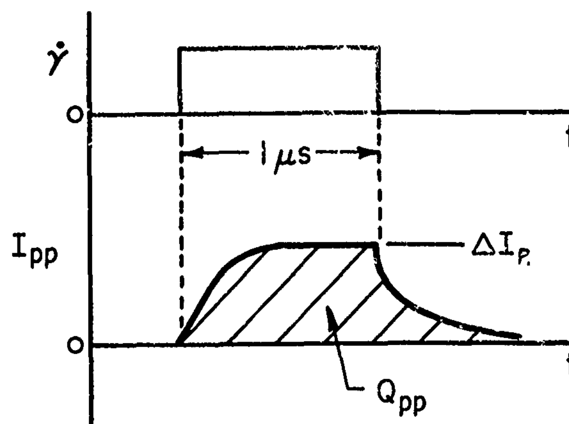


FIGURE 6.17. IONIZING-RADIATION PULSE AND TYPICAL PRIMARY-PHOTOCURRENT RESPONSE

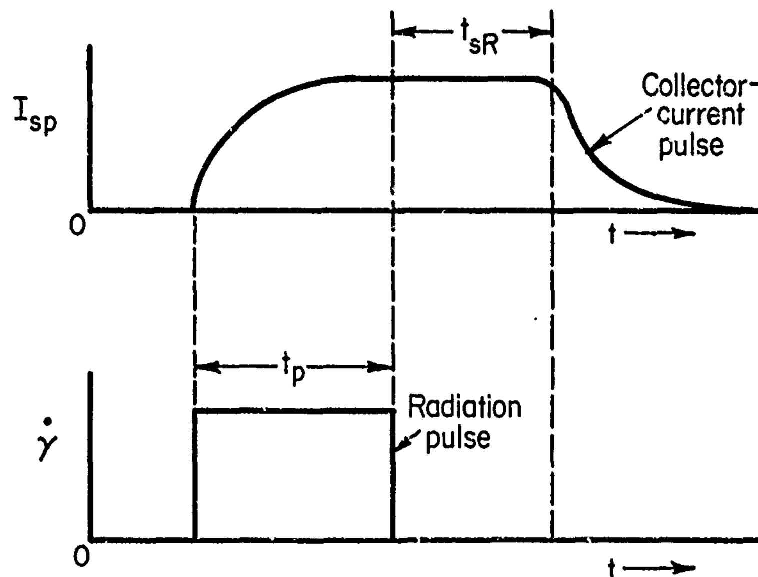


FIGURE 6.18. DEFINITION OF STORAGE TIME

a particular constant dose will be employed as the generalized parameter of a particular PN junction. Note that Q_{pp} for a particular constant dose is essentially a constant independent of the radiation pulse width, while the peak I_{pp} for a particular constant dose rate depends on the radiation pulse width unless steady state is reached (the ratios Q_{pp}/γ and $\Delta I_R/\dot{\gamma}$ are equal). Thus, the radiation response specification in terms of ΔI_R, $\dot{\gamma}$, and relaxation time or Q_{pp}, γ, and relaxation time are equivalent. However, the specification of peak primary photocurrent and peak dose rate is usually not adequate. For numerical presentation, the minimum data requirements include the steady-state photocurrent, the steady-state dose rate, and the device relaxation time or, equivalently, a calculation of the primary photocharge, the radiation dose, and the device relaxation time. In addition, it is important to quote the slope of the curve of steady-state photocurrent versus dose rate, or of photocharge versus dose.

When an operating transistor is exposed to transient ionizing radiation, a current pulse is observed in the external circuit. This current pulse, which may be orders of magnitude larger than that of a diode with comparable dimensions, can reach a peak value at a time later than the radiation peak, and can in some cases continue for times of the order of milliseconds. This characteristic behavior of transistors is the result of the action of the transistor amplifying properties on the primary radiation-induced photocurrents. The electrical action of the transistor creates a secondary photocurrent, I_{sp}, that is produced by the accumulation of excess carriers in the base region as a result of the flow of primary photocurrents across the PN junctions of the device. The steady-state value of I_{sp} is approximately equal to $h_{FE}I_{pp}$ (negligible current flowing out of base lead). The magnitude of I_{sp} can be substantially modified by an external base impedance. The presence of the internal base resistance limits the ultimate reduction of I_{sp}. The amplitude and response duration of I_{sp} also depend on the collector load resistance and depletion capacitance.

Transistors tend to be driven into saturation by pulses of high-intensity gamma radiation, which results in minority-carrier storage. The length of time a transistor remains in saturation is defined as the radiation-storage time, t_{sR}, as illustrated in Figure 6.18. For most transistors, t_{sR} is a function of radiation dose rate and the external base-emitter impedance. I_{sp} and t_{sR} in transistor circuits are often important unknowns, but they can usually be determined with reasonable accuracy using circuit-analysis techniques and a knowledge of device electrical parameters when the primary-photocurrent profiles are known. If measurement of I_{sp} and t_{sR} is required, the radiation response must be measured in the particular circuit application of interest.

Radiation-Source Considerations

The radiation sources considered here are electron linear accelerators (LINAC's) and flash X-ray machines (FXR's). For additional details on radiation sources, the reader is referred to Section 4.

The LINAC is a very flexible machine and thus it is an extremely useful radiation source for characterization of the radiation response of semiconductor devices. A wide range of pulse widths can be obtained, and dose rates can be independently varied over a wide range without changing the sample position or test configuration. For virtually all transistor and diode types, LINAC pulse widths of 0.01 μs result in nonequilibrium photocurrents. However, a 4-μs pulse is several times the dominant minority-carrier lifetime in most transistor and diode types. In such cases, the photocurrent amplitude near the end of the LINAC pulse is a good approximation to the equilibrium (steady-state) value. At high dose rates [$\geq 10^9$ rads (Si or Ge)/s] the LINAC beam diameter is generally too small (0.5 to 2 cm^2 at the beam exit window) to test more than one sample at a time, so tests are normally structured as a sequence of individual measurements.

Flash X-ray machines are available in a variety of maximum voltage ratings, energy delivery capabilities, a wide range of radiation intensities, and beam spacial distributions. With larger machines, it is possible to monitor several components simultaneously. Typically, four to eight samples are monitored, the limitation being primarily on the amount of instrumentation available. Comparative tests between samples exposed in the same burst are readily performed but should be supported by careful dosimetry of each sample. Generally, it is advisable to structure a test to group all similar measurements so that a minimum of operational changes is required. Since the pulse width of most flash X-ray machines is shorter than or comparable to device time constants, nonequilibrium photocurrents are generated in flash X-ray tests.

Test Considerations

There are several aspects of test planning and execution that bear no significant relation to the particular radiation source to be used. Some of these are outlined here as an aid to designing experiments. In addition, the reader is referred to Section 2.5 for a general discussion of test consideration.

Most transistors and diodes are in the class of "thin samples", and their responses are independent of orientation in a homogeneous, high-energy radiation beam. High-power devices, however, may have thick-walled

cases or mounting studs which in some orientations, act to shield the active device volume (semiconductor chip) from the radiation. If such orientations cannot be avoided, the orientation used should be recorded and an effort made to determine the actual dose received by the active volume.

The choice of dose rate(s) at which to irradiate samples is a prime consideration. The choice of the number of dose rates at which to make the measurements will be a function of the particular device (type and manufacturer) and its intended application. In the absence of detailed application information, as a minimum, measurements should be made at each decade of dose rate, $\dot{\gamma}$, over the range of interest. The justification for measurements over a wide range of dose rates is that some devices do not conform to a linear dependence of I_{pp} on $\dot{\gamma}$, and such a series of measurements will reveal the range of rates over which these nonlinearities exist. Certain transistors exhibit superlinear and sublinear dependencies on radiation rate. Usually this behavior is observed at the higher dose rates [$\dot{\gamma} \geq 10^8$ rads (Si)/s].

Except in very-small-geometry devices, for zero volts and forward biases up to approximately 0.6 V for silicon and 0.25 V for germanium, the primary photocurrent flows in the same direction as, and is only slightly less in magnitude than, the photocurrent at 1 volt or so reverse bias. At larger forward biases, the behavior depends on the dose rate and the device material and geometry. For example, if an operating transistor is conducting a relatively large collector current, and it has a collector of high-resistivity material, an electric field will be present in the collector body which will enhance I_{ppc}. Thus, the conventional photocurrent measurements, as described in these procedures, could result in an underestimate of the effect. Hence, the preferred procedures given here do not necessarily apply to the large-forward-bias case. It should be recognized, however, that at least an estimate of I_{pp} under forward-bias conditions is often required in order to obtain a reasonable estimate of circuit responses.

The effective volume for the generation of photocurrent in semiconductor devices includes the space-charge region, hence I_{pp} is weakly dependent on applied voltage (except at voltages near the breakdown voltage where I_{pp} increases sharply because of avalanche multiplication in the junction). If the intended device application is at fixed-voltage bias, measurements of I_{pp} should be made at the specified junction voltage. If no specific operating point is specified, measurements should be made at zero volts and at a voltage approximately 0.8 times the breakdown voltage. If a significant variation is observed, at least two additional measurements should be made at intermediate bias points. At small reverse biases, care must be taken to assure that device saturation does not act to reduce the effective junction bias. Small-signal and switching diodes are likely to exhibit considerable voltage dependence of I_{pp}, and the number of bias points at which measurements are made should be increased as necessary. Measurements should be made at voltages up to approximately 0.8 times the diode breakdown voltage.

In cases where an accurate representation of transistor radiation response is required for circuit-response calculations (e.g., by computer), accurate profiles of $I_{ppc}(t)$ and $I_{ppe}(t)$ are required. Consider the measurement of $I_{ppc}(t)$. This measurement is commonly performed with the emitter lead open. Since ionizing radiation induces photocurrents across both junctions, I_{ppe} will flow and charge the intrinsic base-emitter capacitance of the device, thus tending to forward-bias that junction. If a significant forward bias is developed, transistor operation will begin, and the measured current will consist of two components - I_{ppc} and a current proportional to I_{ppe}. Thus, the measured current may not accurately represent the collector-base photocurrent. An analogous situation exists for the measurement of I_{ppe}.

From an engineering standpoint, the error introduced into an I_{ppc} measurement when the emitter lead is open is seldom signficant, since $I_{ppe} \ll I_{ppc}$ for most geometries. The error introduced into an I_{ppe} measurement when the collector lead is open is insignificant if the inverted common-base current gain (α_I) is very small. One obvious exception is the alloy-junction geometry, for which α_I is often greater than 0.5. It is the respons'bility of the experimentalist to assure that resulting errors are negligible. As a means of reducing the magnitude of the error, measurements can be made with both junctions reverse biased, thus prohibiting transistor action. If this is done, the voltage-bias conditions should be reported in test results.

In field-effect devices, a proper drain-photocurrent measurement, I_{ppd}, requires the source be shorted to the drain. If the source is open-circuited, additional current flow in the drain circuit due to the source photocurrent, I_{pps}, is observed. Since ionizing radiation induces photocurrents across both drain and source junctions, I_{pps} will flow through the channel region and add to the observed photocurrent. At low currents where I_{pps} is less than the maximum channel current, the observed drain current is equal to the sum of $I_{ppd} + I_{pps}$ (for symmetrical devices, the current is twice I_{ppd}). At high currents where I_{pps} is greater than the channel can supply, the observed current is limited to the sum of I_{ppd} and the maximum channel current.

Spurious Currents

The radiation sources and fields used in TREE experiments can act as a source of spurious currents. The currents arising from air ionization, secondary emission and cable currents are important in semiconductor-device testing since these currents effectively place a lower limit on the magnitude of signal photocurrents that can be measured accurately. These sources of "noise" must be eliminated or accounted for in all device testing. A discussion of noise suppression is included in Section 2.5.

Any sample that exhibits a photocurrent at a given dose rate which is less than eight times the total spurious current at that dose rate and at that facility is defined as a "small responder". Typical spurious current levels indicate that devices whose steady-state photocurrent is at least 10^{-11} A/[rad(Si)· s] present no particular difficulty from spurious currents. Devices whose steady-state photocurrent response is between 10^{-12} and 10^{-11} A/[rad(Si)· s] may be small responders, depending on the care exercised in minimizing spurious currents. Devices whose steady-state photocurrents are less than 10^{-12} A/[rad(Si)· s] should be considered small responders. Individually tailored experimental procedures and measurements are required to reduce the noise level in radiation tests on small responders to a level such that useful photocurrent measurements can be made. Typically, small responders are small area diodes and transistors (gold doped) and integrated-circuit kit parts whose junction area is approximately 12 square mils or less. It should be realized that junction photocurrents on small responders may be extremely difficult to measure.

Whenever measurements are made on a small responder, the radiation beam area should be reduced as small as possible by either proper collimation of the beam or proper focusing to minimize the replacement current. The sample and the associated wires should be encapsulated with at least a 1/8-inch coating of paraffin, glyptol, or silastic rubber to decrease the air ionization currents. (Normally, air ionization currents are significant for field-effect devices even though the device is a large responder, since the gate terminal of these devices is a high impedance point.) Of course, all techniques of good high-frequency design are required to maximize the signal-to-noise ratio (see Section 2.5).

The magnitude of the spurious currents can be estimated by an experiment where a dummy sample (with no active element) is mounted near the test sample and the current it exhibits is measured. However, extreme care must be taken to insure that the resulting geometries, potentials, and impedances adequately simulate the nonactive portion of the sample of interest. By measuring the radiation-induced current in both the voltage and ground lead of the sample (two-lead measurement method), there is a better possibility of determining the true junction photocurrent. The difference between the two measured currents provides a rough indication of the problems associated with the measurement. This method does not reveal any current component that flows in parallel with the signal current. However, such a current would result primarily from an ionization effect, and this would be reduced somewhat by potting. If line drivers are required, they should be carefully designed. They generally require severe tradeoffs between linearity, input impedance, signal swing capability, and capacitive loading. Differential measurements can also be used; however, the application of differential techniques to narrow, fast-rise-time radiation testing is not straightforward (see also Section 2.5).

Preferred test circuits are given here for the measurement of semiconductor-junction primary photocurrent, I_{pp}. Two basic techniques are illustrated – the resistor-sampling method and the current-probe method. Either one- or two-lead measurements are applicable to either of these basic techniques. In addition, a resistor sampling circuit applicable for field-effect devices is illustrated. Although the measurement techniques for field-effect transistors are essentially the same as those for bipolar transistors and diodes, some specific procedures and precautions are given to complement the basic measurement techniques as they apply to field-effect devices. The following procedures deal mainly with the electrical aspects of the tests; they do not alone constitute complete procedures for testing at a particular radiation facility. Other sections of this document exist to complement the procedures given below. Section 2.5 on noise suppression is particularly applicable to these procedures. The various methods of noise suppression must be considered in the design of transient-radiation-effects experiments on semiconductor devices.

Adequate documentation of the methods and results of transient-effects experiments cannot be overly stressed. The following data should be recorded for each radiation burst. Additional procedures outlining the format for data reporting are given in Section 6.3.

- Identification of all test equipment, including accuracy and scale factors
- Circuit used
- Exact experimental configuration, including shielding and grounding schemes
- Type of ionizing radiation
- Energy spectrum of the incident radiation
- Voltage bias on the sample
- Radiation-pulse shape
- Radiation-pulse width
- Dose rate in the sample material
- Accumulated dose in the sample material
- Sample orientation and case connection

- Ambient temperature
- Pictorial representation of $I_{pp}(t)$
- Photocharge, Q_{pp}, or steady-state photocurrent, ΔI_R, if attained
- Device relaxation time.

It is important to note that, in the following test circuits, the single-point grounding philosophy is recommended whenever possible. If the requirement for adjustment of bias voltage from the instrumentation room does not exist, the power-supply cables can be eliminated by the use of batteries located in the exposure room. When used, these batteries should be well shielded from the radiation. Large values of capacitance are recommended for power-supply bypass (shunted by a small value low-inductance disc capacitor). These capacitors function to carry the radiation-induced current transient which may not be supplied by the bias source. The capacitance must be sufficiently large to prevent a temporary "slump" in supply voltage. In general, lead lengths should be as short as possible to minimize inductance. Resistors and capacitors with suitable high-frequency characteristics should be used. In addition, all wiring and components should be RF shielded and cables should be bundled together.

Resistor-Sampling Methods

The primary photocurrent may be measured by sampling the voltage across a resistor that is in series with the sample. This technique is used when maximum sensitivity is required or when the time duration of the transient current exceeds the pulse-width capability of current probes. It has the disadvantage of causing circuit saturation of Ipp at very high dose rates owing to an effective reduction of the reverse bias across the junction. The tendency toward circuit saturation may be reduced by reducing the value of the resistance.

To increase the sensitivity of the photocurrent measurement, the sampling resistor must be increased, which causes a mismatch between the resistor and the cable. In this case, the test circuits should be modified to include an impedance matching device such as a cathode follower. The cathode follower should be located as closely as possible to the sample to preserve the frequency response and should be well shielded from the radiation environment. The precautions listed in Section 2. 5 should be considered to minimize problems associated with loading, cable matching, and frequency response.

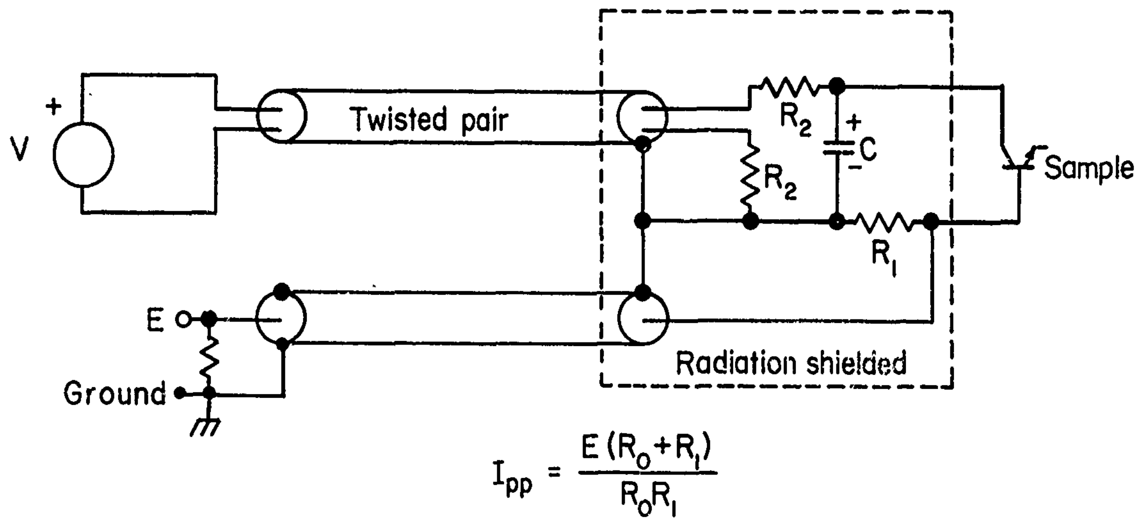
Figure 6.19 describes a one-lead measurement. The circuit components in this figure are defined as follows:

- V – An adjustable voltage source to set the required bias
- R_0 – The cable characteristic resistance
- R_1 – The sampling resistor
- R_2 – Selected to give high-frequency isolation
- C – An effective bias-supply bypass (the time constant $2R_2C$ should be larger than any time constant of interest)
- E is photographed on a suitable oscilloscope.

R_1, R_2, and C must be located near the test sample for the proper frequency-response characteristic. Measurements should be made on the lead having the smaller mass associated with it. This tends to minimize spurious currents. For example, when making I_{ppc} measurements on an NPN transistor, the voltage source V should be connected to the collector and the base should be connected to the center conductor of the coax.

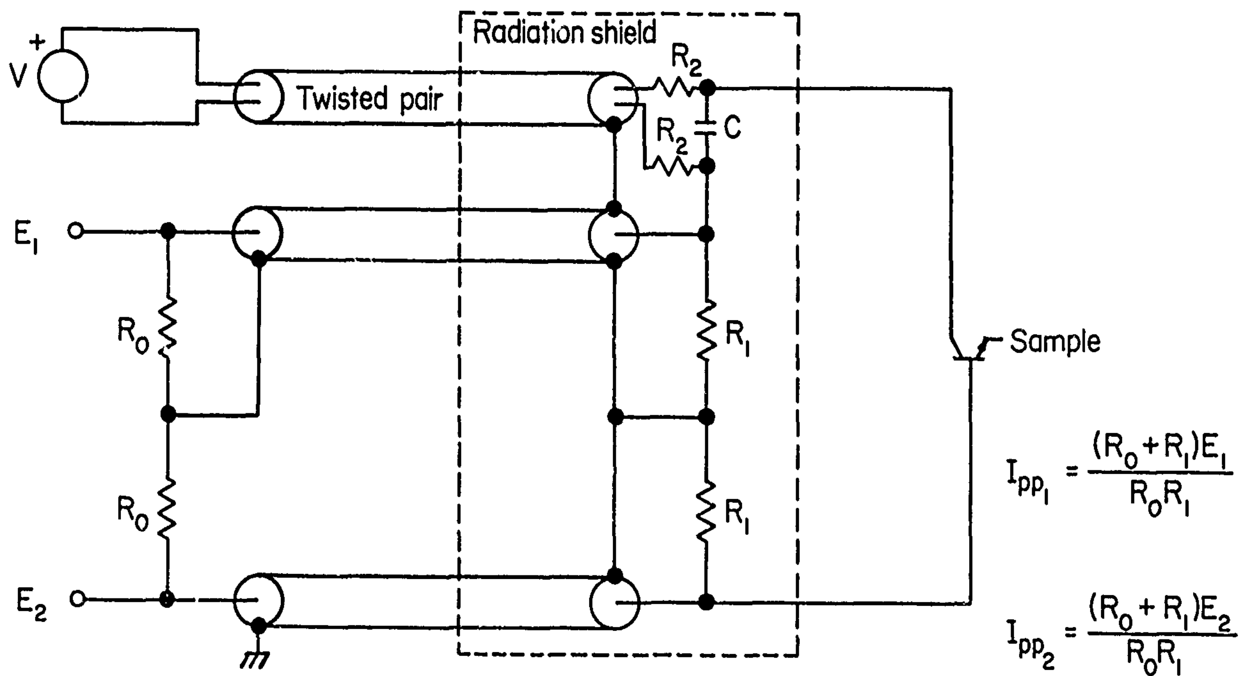
In order to measure the radiation current in both the ground lead and voltage lead of the sample, the circuit configuration shown in Figure 6.20 is recommended. The circuit is intended for use in experiments where large charge emission currents are expected (flash X-ray machines). This circuit eliminates noise in the output cables and the spurious signal due to the symmetric component of charge emission. It does not, however, eliminate any unsymmetric component of the charge emission. Thus, the difference between the signal in the voltage lead and the ground lead of the sample provides a rough indication of the problems associated with spurious currents. The circuit components in Figure 6.20 are defined as follows:

- R_0 – The cable characteristic resistance
- C – An effective bias-supply bypass (the time constant $2R_2C$ should be larger than any time constant of interest)
- R_1 = R_0 for best pulse fidelity (for improved sensitivity increase $R_1 > R_0$ and use a cathode follower)
- V – An adjustable voltage source set to the required bias



$$I_{pp} = \frac{E(R_0+R_1)}{R_0 R_1}$$

FIGURE 6.19. ONE-LEAD, RESISTOR-SAMPLING I_{pp} MEASUREMENT



$$I_{pp_1} = \frac{(R_0+R_1)E_1}{R_0 R_1}$$

$$I_{pp_2} = \frac{(R_0+R_1)E_2}{R_0 R_1}$$

FIGURE 6.20. TWO-LEAD, RESISTOR-SAMPLING I_{pp} MEASUREMENT

- R_2 – Selected to give high frequency isolation
- E_1 and E_2 are photographed on a suitable oscilloscope.

R_1, R_2, and C must be located very near the test sample in order to obtain the necessary frequency-response characteristics.

Current-Probe Methods

The primary photocurrent may be measured directly by using a current probe (current transformer). This technique is used when minimum deviation of the operating point is required. Although this method of measuring photocurrent is less sensitive than the previous method (1 mV/mA), it is capable of measuring larger photocurrents. The upper limit of the measurement can be made dependent only upon the saturation limit of the current probe. The low-frequency cutoff of such probes may make them inadequate for wide pulse widths.

The circuit configuration for one-lead measurement is shown in Figure 6.21. The circuit components in Figure 6.21 are defined as follows:

- V – An adjustable voltage source set to the required bias
- R_0 – The cable characteristic resistance
- R_2 – Selected to give high-frequency isolation
- C – An effective bias-supply bypass (the time constant $2R_2C$ should be greater than any time constant of interest)
- CT – A current probe with suitable response characteristics
- I_{pp} is photographed on a suitable oscilloscope.

A small damping resistor may be required in series with the sample since the inductance of the current probe and the capacitance of the sample, together with the bias source, can behave as a tank circuit. If these conditions are allowed to develop, the observed response will exhibit ringing. A compromise between desired high-speed response and the reduction of oscillation must be sought with this circuit. Further, if the pulse transit time from the capacitor to the sample is comparable to or less than the rise time of I_{pp}, the connecting leads act as a transmission line which is not terminated in its characteristic impedance. To minimize the effects of this reactive impedance, it is desirable to keep these interconnecting leads as short as possible. The ground lug on the current probe must be properly connected to signal ground.

The proximity of the capacitor to the sample requires that the capacitor exhibit minimum radiation response. Since the radiation response of both the capacitor and the current probe would perturb the observed response, they should be selectively shielded from the radiation.

Figure 6.22 describes a two-lead measurement for use in experiments where large charge emission currents are expected. The circuit components are defined as follows:

- V – An adjustable voltage source set to the required bias
- R_0 – The cable characteristic resistance
- R_2 – Selected for high-frequency isolation
- C – An effective bias-supply bypass (the time constant $2R_2C$ should be greater than any time constant of interest)
- CT – A current probe with suitable response characteristics
- I_{pp1} and I_{pp2} are photographed on a suitable oscilloscope.

A small damping resistor may be required in series with the sample to minimize ringing. The current probes and capacitor must be located very near the test sample in order to obtain the necessary frequency-response characteristics.

The measurement circuits illustrated in Figures 6.19, 6.20, 6.21, or 6.22 can be adapted for the measurement of secondary photocurrent and radiation storage time. The measurement involves interchanging the emitter and base terminal of the transistor in the primary-photocurrent test circuit. External base and collector resistors are added as indicated by the basic data requirements. Unless specific data requirements dictate otherwise, it is suggested that the base terminal be connected to the emitter through a high-resistance (minimum stray capacitance) circuit such that the current flowing out of the base is a negligible portion of the total base current ($R_B \sim 10^5$ ohms). In addition, measurements should be made with a minimum collector resistance required to obtain an accurate sample of the collector current. Care should be exercised in the construction of the secondary photocurrent test circuit to minimize the stray capacitance at the base and collector terminals of the device under test. In particular, the capacitance associated with the external base resistance must be minimized to reduce the time constant of the base circuit.

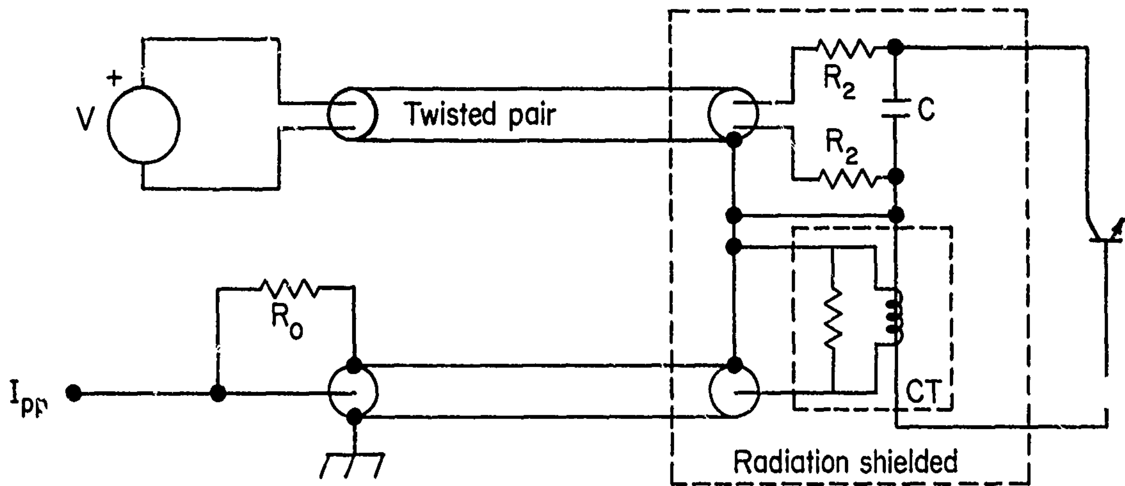


FIGURE 6.21. ONE-LEAD, CURRENT-PROBE I_{pp} MEASUREMENT

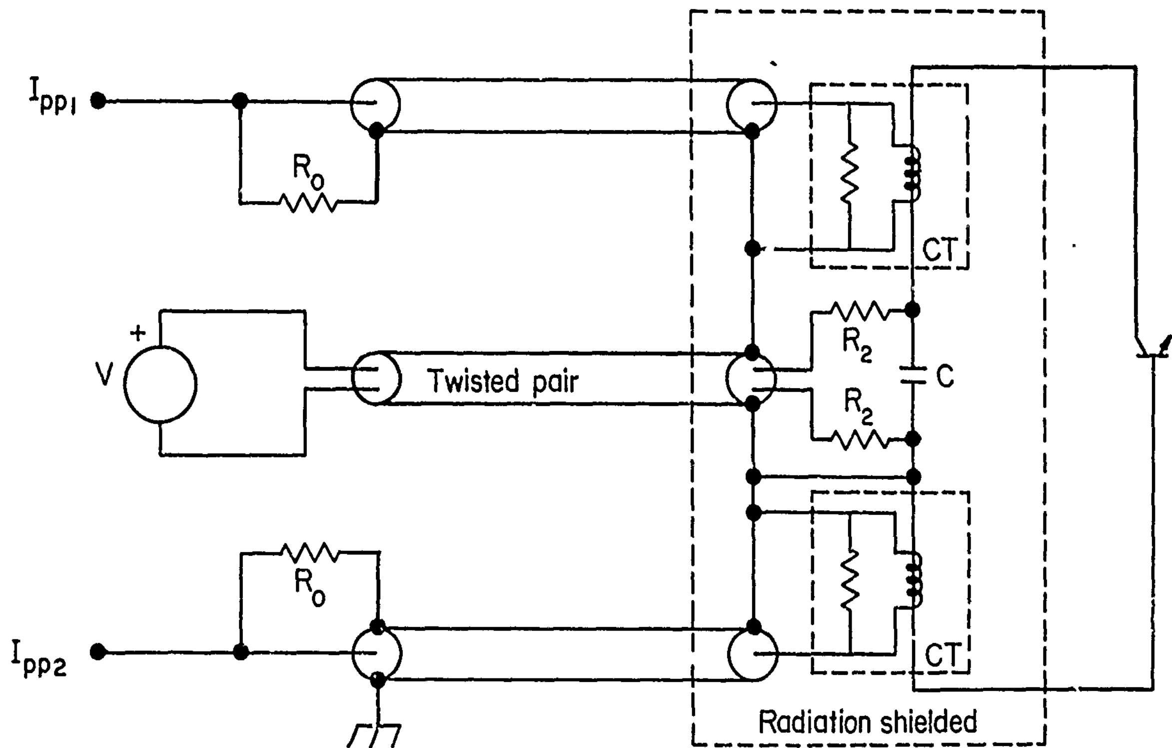


FIGURE 6.22. TWO-LEAD, CURRENT-PROBE I_{pp} MEASUREMENT

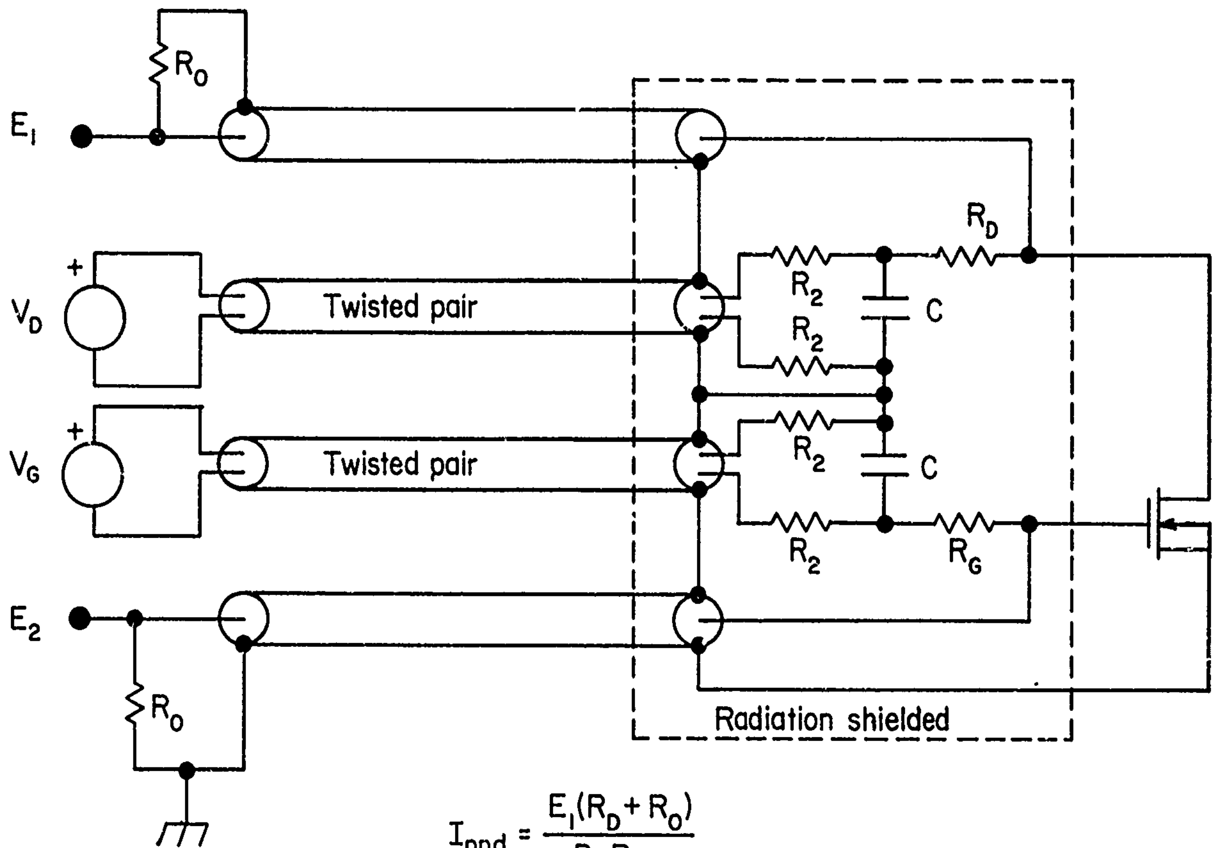
Measurement Method for FET's

As in the case of bipolar transistors and diodes, the most valuable ionization-effects data that can be made available to designers are specifications of the primary photocurrents as a function of time at various conditions of bias and various ionization dose-rate profiles. In field-effect transistors it is necessary to specify the response of the channel and the influence of charge emission and ionization currents generated in the gate circuit (package response) in addition to the primary photocurrent. The package response influences the drain current by gain action in the field-effect device.

In general, the drain photocurrent and the channel response can be measured independently from the package response by irradiating samples where secondary-emission and air-ionization currents are minimized. The package response can be independently determined by irradiating "dummy packages". These devices consist of FET metallization pattern put down on an oxidized silicon chip and encapsulated in identical packages as the active samples. The effects of secondary emission can be reduced to a negligible level by careful selective radiation shielding such that the radiation dose rate is attenuated at all points of the test fixture except for the device under exposure. In addition, by using short lead lengths and aligning all leads (those going to and from the sample that are exposed to the radiation beam) perpendicular to the beam, the secondary-emission currents can be minimized. To reduce air-ionization currents, devices should be potted in paraffin or another suitable potting material (the paraffin should be coated with conducting paint to preserve RF shielding integrity). In addition, the techniques on low-noise construction discussed in Section 2.5 should be incorporated in the experimental design. These include complete RF shielding of the sample and circuitry, single-point grounding scheme, floating power supplies (or the use of batteries located in the shielded radiation fixture), short lead lengths to minimize inductance, and localized metallic-foil shielding to minimize internal EMP pickup.

Figure 6.23 describes a circuit for measurement of the transient drain and gate currents of field-effect devices. The circuit can be used for measurements on JFET and MOSFET devices. The circuit componets in Figure 6.23 are defined as follows:

- V_D – Drain voltage bias supply
- V_G – Gate voltage bias supply
- R_D – Sampling resistor in series with drain lead
- R_G – Sampling resistor in series with gate lead
- R_0 – Cable characteristic resistance
- R_2 – Selected for high-frequency isolation



$$I_{ppd} = \frac{E_1(R_D + R_O)}{R_D R_O}$$

$$I_{ppg} = \frac{E_2(R_G + R_O)}{R_G R_O}$$

FIGURE 6.23. DRAIN AND GATE TRANSIENT RESPONSE MEASUREMENT CIRCUIT FOR FET DEVICES

- C – Power-supply bypass capacitors (the time constant $2R_2C$ should be greater than any time constant of interest)

- E_1 and E_2 are photographed on a suitable oscilloscope.

The data to be recorded for each radiation burst are outlined at the beginning of this section.

It is important to keep the sampling resistor in the drain circuit as small as possible to avoid causing circuit saturation of I_{pp} at high dose rates owing to an effective reduction of the bias voltage across the junction. If the voltage drop across R_D is more than 10 percent of the supply voltage, the sampling resistor should be reduced or replaced by a current probe. To increase the sensitivity of the measurement circuit $R_D > R_0$ may be required. In this case a cathode follower should be used to match impedance between the cable and the sampling resistor. The sampling resistor, R_G, must also be selected as small as possible to prevent flow of secondary photocurrent. In JFET devices, the transient gate current is approximately twice the drain current (since the source photocurrent also flows in the gate lead). In MOSFET devices, the photocurrents are generated by the drain- and source-substrate junctions, and thus only the dielectric-response, air-ionization, and secondary-emission currents flow in the gate lead.

The major bias conditions of interest in field-effect devices are the pinch-off and cutoff regions. The drain photocurrent is measured in the cutoff region ($V_D = 0, V_G$ variable beyond the threshold voltage). The channel response is measured by biasing the FET device in the pinch-off region. The measured current in the drain lead is then the sum of drain photocurrent and the channel response. Secondary photocurrents can be measured by varying the drain and gate resistance. Note that the source terminal is connected to the drain when making drain-photocurrent measurements. If the source is left floating, the magnitude of the drain current will increase owing to the source photocurrent.

6.3 DATA REPORTING

General

The general information required in most reports of TREE tests are given in Section 3.0, "Documentation Requirements". Information requirements covered in that section include reporting of the experimental procedure, a description of the facilities used, the documentation of the dosimetry, and a complete description of the samples irradiated. Included in this subsection are specific data requirements for tests involving transistors and

diodes and standardized formats for reporting the data. Table 6.4 shows a typical data format that can be used to present the general information for each irradiation test.

In addition to the irradiation procedure, basic types of samples should be described. A good technique is having a distinct data sheet that presents for the various device types the manufacturer, type or specification number, lot number, origin (factory, distributor, etc.), and method of selection and validation. If useful electrical and structural information (such as power rating and junction areas) is available, it should be reported to facilitate data comparisons and to increase the general utility of the data. A typical parts tabulation sheet is illustrated in Table 6.5.

A statement should be given as to the constancy of any control samples used. The estimated uncertainty in all important results should be quoted. In specifying errors, the value of one standard deviation is the quantity preferred, although other methods may be used if they are more suitable and are unambiguous. When statistical characterizations are given, at least a reference should be cited which explains the techniques involved in their calculation.

Permanent-Damage Data

It is recommended that device parameter data be tabulated for each measurement set, giving the parameter measured, the irradiation level at which the measurement was made, and the operating condition of the device during measurement. Note that preirradiation parameter values must be included. Usually the preirradiation measurements performed on the test device are of two types: those in which important radiation-induced changes are expected to occur (see Tables 6.2 and 6.3) and other measurements which may help to characterize the device. In addition to these measurements, it is desirable to perform other measurements by which the particular device can be characterized (these measurements are usually performed before the devices are irradiated). Exemplary data formats for tabulating measured parameter values are given in Tables 6.6, 6.7, and 6.8 for diodes, bipolar transistors, and field-effect devices. As supplementary information to parameter data, the measurement procedure should be reported. Specifically this includes the measurement-circuit diagram, a list of the measurement equipment, a statement regarding the accuracy and/or precision of the data, etc.

Graphs showing the radiation-induced changes in the measured parameter values are very desirable and complement the tabulated data. The method employed for the graphical presentation of data depends on the method of data analysis and the objectives of the experiments. As a general guideline, it is recommended that parameter measurements made at only one

TABLE 6.4. GENERAL INFORMATION

Device Type(s): ______________________________

Facility: ______________________________ Date of Test: __________

Dosimetry Method(s): ______________________________

Irradiation Temperature: ______________________________

Experimental Configuration: ______________________________

Electrical Condition During Irradiation: ______________________________

(Specify device bias condition and the circuit diagram, including all test equipment and grounding scheme used during *in situ* measurement.)

Additional Comments:

TABLE 6.5. PARTS TABULATION

Information to be Included				Useful Information					
Serial No.	Unit Designation in Test	Manufacturer	Date of Manufacture and/or Purchase	Device Batch and Lot No.	Maximum Current Rating	Maximum Voltage Rating	Junction Area(s)	Device Application	Comments

TABLE 6.6. DIODE PERMANENT-EFFECTS DATA

Device Type: ____________________

Date: ____________________

Unit Desig	V_F at I_F		I_R at V_R		V_Z, ΔV_Z at I_Z			t_r at I_F I_R			Neutron Fluence	Total Dose	Temp
	V	mA	μA	V	V	V	mA	μs	mA	mA	n/cm^2 (1-MeV Eq.)	rad(Si)	C

TABLE 6.7. BIPOLAR-TRANSISTOR PERMANENT-EFFECTS DATA

Device Type: ______________________

Date: ______________________

Unit Desig	Parameters									Test Conditions									Neutron Fluence	Total Dose	Com-ments
	h_{FE} h_{fe}	$V_{CE(SAT)}$ $V_{BE(SAT)}$	I_{CBO} I_{EBO}	V_{BE}	f_T	t_r	t_f	t_s	BV_{CBO} BV_{EBO} BV_{CEO}	I_C	I_E	I_B	V_{CE}	V_{CB}	V_{EB}	$\frac{I_C}{I_B}$	Freq.	Temp			
		V	nA	mV	MHz	μs	μs	μs	V	mA	mA	mA	V	V	V		Hz	C	n/cm^2 (1-MeV Eq.)	rad(Si)	

TABLE 6.8. FIELD-EFFECT-TRANSISTOR PERMANENT-EFFECTS DATA

Device Type: ______________________

Date: ______________________

Unit Desig	Parameters					Test Conditions						Neutron Fluence	Gamma Dose	Com-ments
	I_{DSS} $I_{DS(ON)}$	V_T	g_m	I_{GSS} $I_{DS(OFF)}$	$V_{DS(ON)}$	V_{DS}	V_{GS}	I_D	Freq.	T	V_{GS} During Expo-sure*			
	mA	V		mA	V	V	V	mA	Hz	C	V	n/cm^2 (1-MeV Eq.)	rad(Si)	

*For MOSFET devices.

operating point should be plotted as a function of radiation exposure. Parameters that are measured at several operating points at each fluence level should be plotted as a function of the parameter varied to change the operating point. The result will be a family of curves for the various radiation exposures.

Figure 6.24 shows an example of h_{FE} curves. h_{FE} is plotted as a function of collector current prior to irradiation and at the two neutron fluences at which measurements were made. To aid in interpolation, it would be helpful to show intermediate fluence levels between curves at one or more current values such as the 10^{12} n/cm^2 point at I_C = 10 mA in Figure 6.24. These points can be determined by interpolating on a curve of h_{FE} versus neutron fluence at a selected current level. For devices used in linear circuit applications, it is also recommended that the originator of the data present curves of h_{fe} (small-signal values) versus I_C versus Φ, as well as the h_{FE} data.

Similar methods can be used to report permanent-effects data on field-effect devices and diodes. In particular, a curve showing the change in threshold voltage, ΔV_T, as a function of the gate bias (during irradiation) at several gamma dose levels is recommended for radiation tests on MOSFET devices. Permanent-effects data on diodes could include a family of curves showing the forward voltage versus forward current at various neutron fluences.

Consideration should also be given to calculating the constants for the radiation-damage models which are presently being used (i.e., the lifetime damage constant or the carrier-removal damage constant).

Ionization-Effects Data

It is recognized that data types and accuracy requirements vary greatly over the range of possible design and analysis criteria. Usually, a designer is most interested in:

- Primary photocurrent, I_{pp}, or photocharge, Q_{pp}
- Secondary photocurrent, I_{sp}, and radiation-storage time, t_{sR} (for circuit design or operating point)
- Device relaxation time.

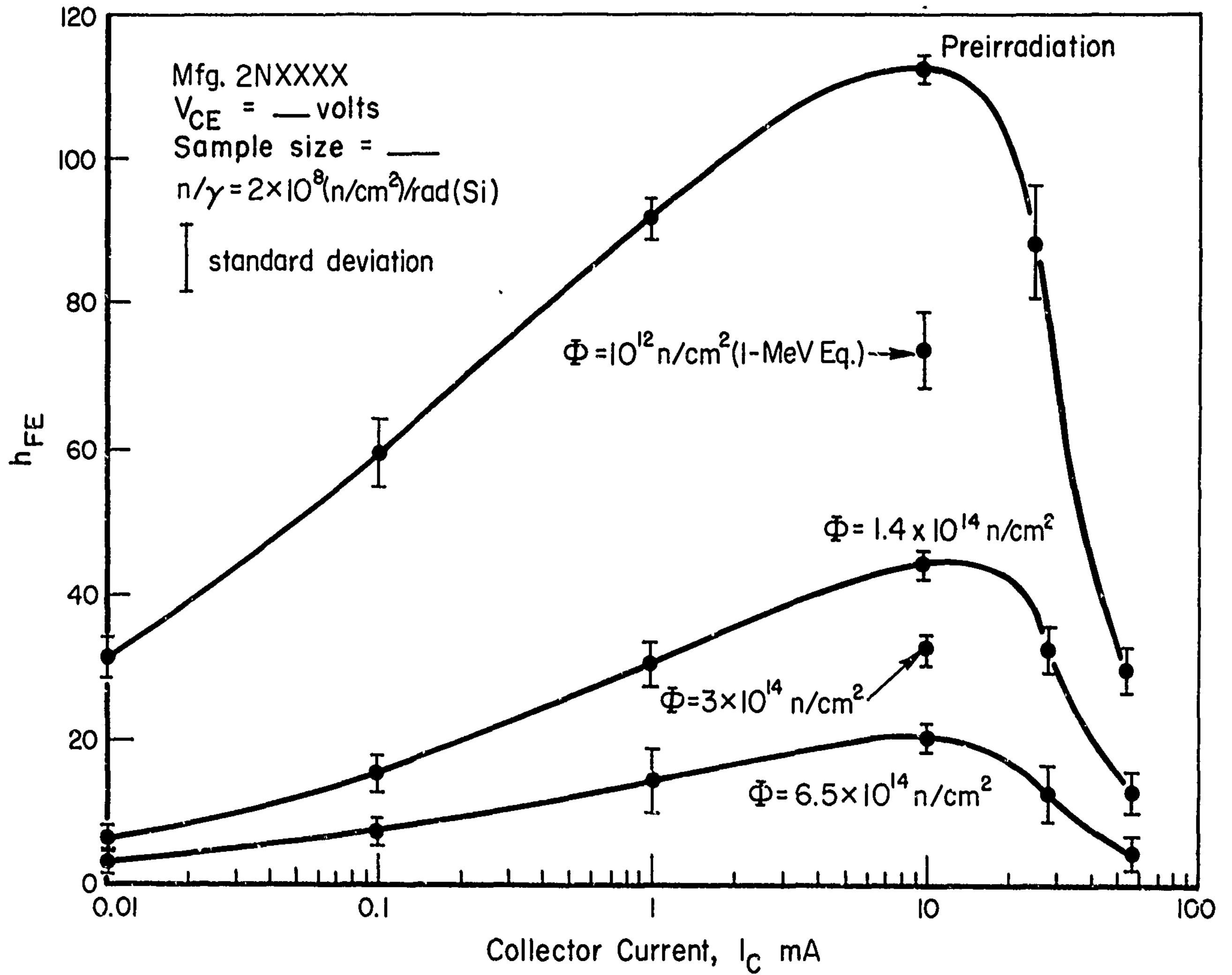


FIGURE 6.24. RECOMMENDED FORMAT FOR REPORTING h_{FE} PERMANENT-DAMAGE DATA

The analyst, with access to various models, is most interested in primary-photocurrent statistical distribution, time history, and variation with other parameters. The data to be presented for general utility are:

- I_{pp} as a function of time
- Equilibrium (steady-state) I_{pp} versus $\dot{\gamma}$ and device relaxation time
- Q_{pp} versus γ and device relaxation time
- I_{pp} or Q_{pp} versus voltage
- Equilibrium I_{sp} and t_{sR} versus $\dot{\gamma}$.

The measured ionization response of semiconductor devices should be tabulated in a fashion similar to the format described for permanent-effects data. Exemplary data formats for tabulating ionization data are given in Tables 6.9, 6.10, and 6.11 for diodes, bipolar transistors, and field-effect devices. As additional useful information, consideration should be given to reporting complementary electrical-characterization data (measured before irradiation exposure) that are likely to be correlated with the radiation response. An example of such data would be the electrical storage time of a transistor, or any other parameter dependent on the collector lifetime.

The graphical presentation of ionization-effects data as a complement to tabulated data is very desirable. A typical format for the graphical presentation of steady-state primary photocurrent, I_{pp}, as a function of ionizing-radiation dose rate is shown in Figure 6.25. For each device type on which ionizing-radiation data are reported, there should be an illustration showing a typical response as a function of time and displaying the leading and trailing edges of the pulse. The pulse shape should be given in sufficient detail to permit pulse-width scaling of peak photocurrent. The dose rate at which the illustration was taken should be indicated on the I_{pp} versus $\dot{\gamma}$ curve. In the event the shape of the I_{pp} response changes appreciably with dose rate, additional illustrations of response should be shown, and areas of the response curve (I_{pp} versus dose rate) to which they apply should be indicated.

TABLE 6.9. DIODE IONIZATION DATA

Device Type: ______________________

Date: ______________________

Unit Desig	Rev. Bias	I_{pp}	Q_{pp}	τ	t_{sR}	I_Z	V_Z	ΔV_Z	Dose Rate	Dose	Pulse Width	Comments
	V	mA	Q	μs	μs	mA	V	V	rad(Si)/s	rad(Si)	μs	

TABLE 6.10. BIPOLAR-TRANSISTOR IONIZATION DATA

Device Type: ______________________

Date: ______________________

Unit Desig	V_{CB}	V_{EB}	I_{ppc}	I_{ppe}	Q_{ppc}	Q_{ppe}	τ_{CB}	τ_{EB}	I_{sp}	t_{sR}	Dose Rate	Dose	Pulse Width	Comments
	V	V	mA	mA	Q	Q	μs	μs	mA	μs	rad(Si)/s	rad(Si)	μs	

TABLE 6.11. FIELD-EFFECT TRANSISTOR IONIZATION DATA

Device Type: ____________________

Date: ____________________

Unit Desig	V_D	V_G	I_{ppd}	I_{ppg}	Q_{ppd}	Q_{ppg}	τ_D	τ_G	I_{sp}	t_{sR}	Dose Rate	Dose	Pulse Width	Comments
	V	V	mA	mA	Q	Q	μs	μs	mA	μs	rad(Si)/s	rad(Si)	μs	

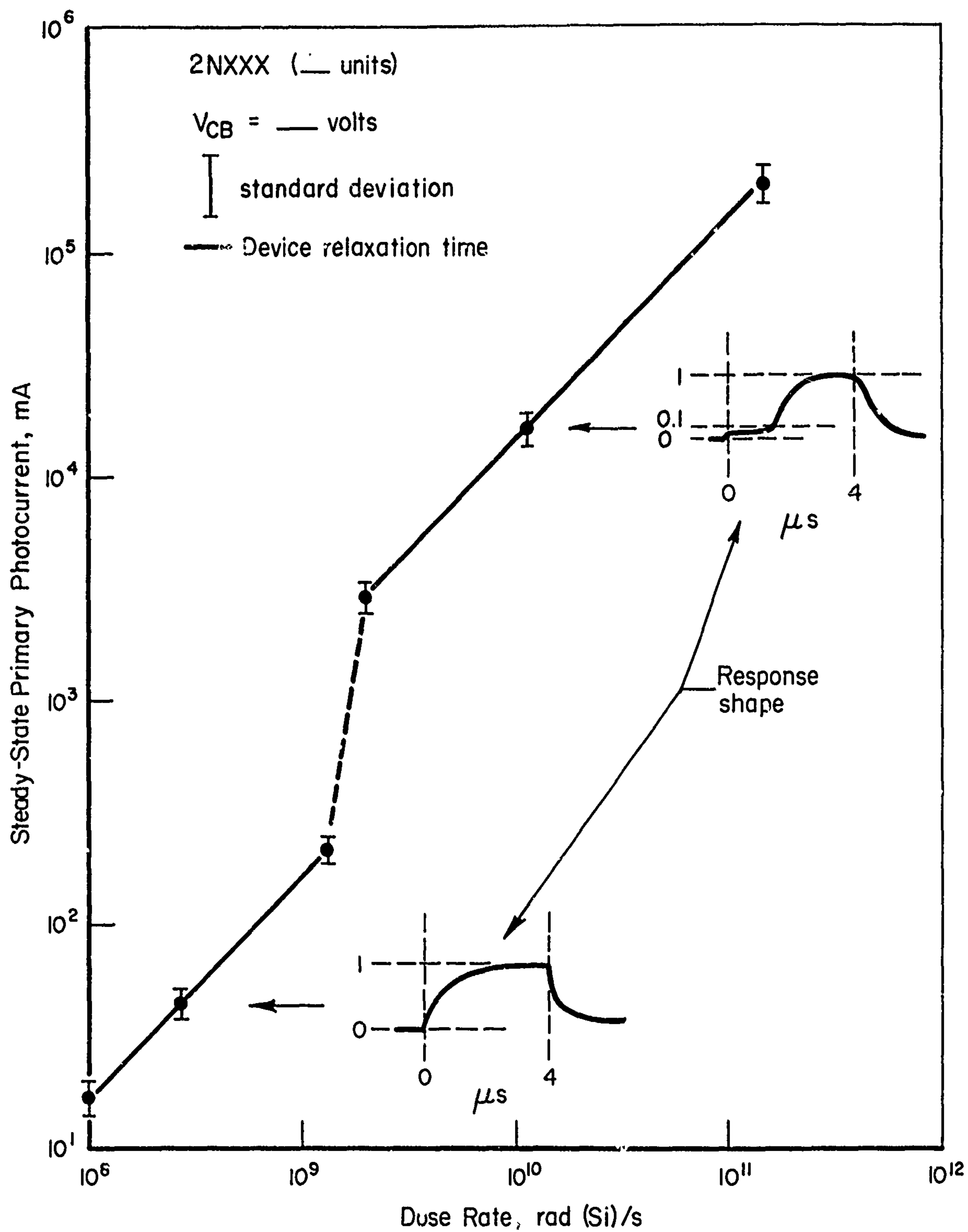


FIGURE 6.25. RECOMMENDED FORMAT FOR REPORTING PRIMARY-PHOTOCURRENT DATA

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7.0 CAPACITORS

7.1 SCOPE

This section deals with experimental procedures for determining the currents and voltages in charged and uncharged capacitors exposed to a transient radiation environment. While permanent changes such as degradation of the dielectric or physical distortion of the capacitor are observed in some capacitor parameters, the most important effects are associated with ionization within the capacitor structure and are, therefore, transient. No attempt is made in this section to describe the mechanisms of the capacitor response, but it is recommended that the user of these procedures acquaint himself with the Section 7 items of the bibliography so that the limitations of extrapolating these techniques, as well as the importance of the precautions given in this section, can be appreciated.

7.2 PARAMETERS TO BE MEASURED

Conductivity

For the most common capacitance values, the predominant effect on a charged capacitor exposed to radiation is the induced conductivity in the capacitor dielectric. An exception to the dominance of the conductivity has been observed in capacitors with very low capacity (10 to 1000 pF), where the secondary-emission signal (covered under Subsection 7.3) may be larger than the conductivity signal. The radiation-induced conductivity tends to cause a discharge of the capacitor, producing a current in the capacitor-charging circuit. Both the magnitude and the time dependence of this conductivity are of interest.

Figure 7.1 shows currents in a typical charged capacitor resulting from radiation photoconductivity response due to a square pulse of radiation. The photoconductivity response is usually divided into prompt and delayed components. The prompt component occurs simultaneously with the radiation and disappears at the termination of the pulse. Delayed components persist following the cessation of radiation, decaying with characteristic relaxation times which may be a function of the dose delivered by the radiation pulse.

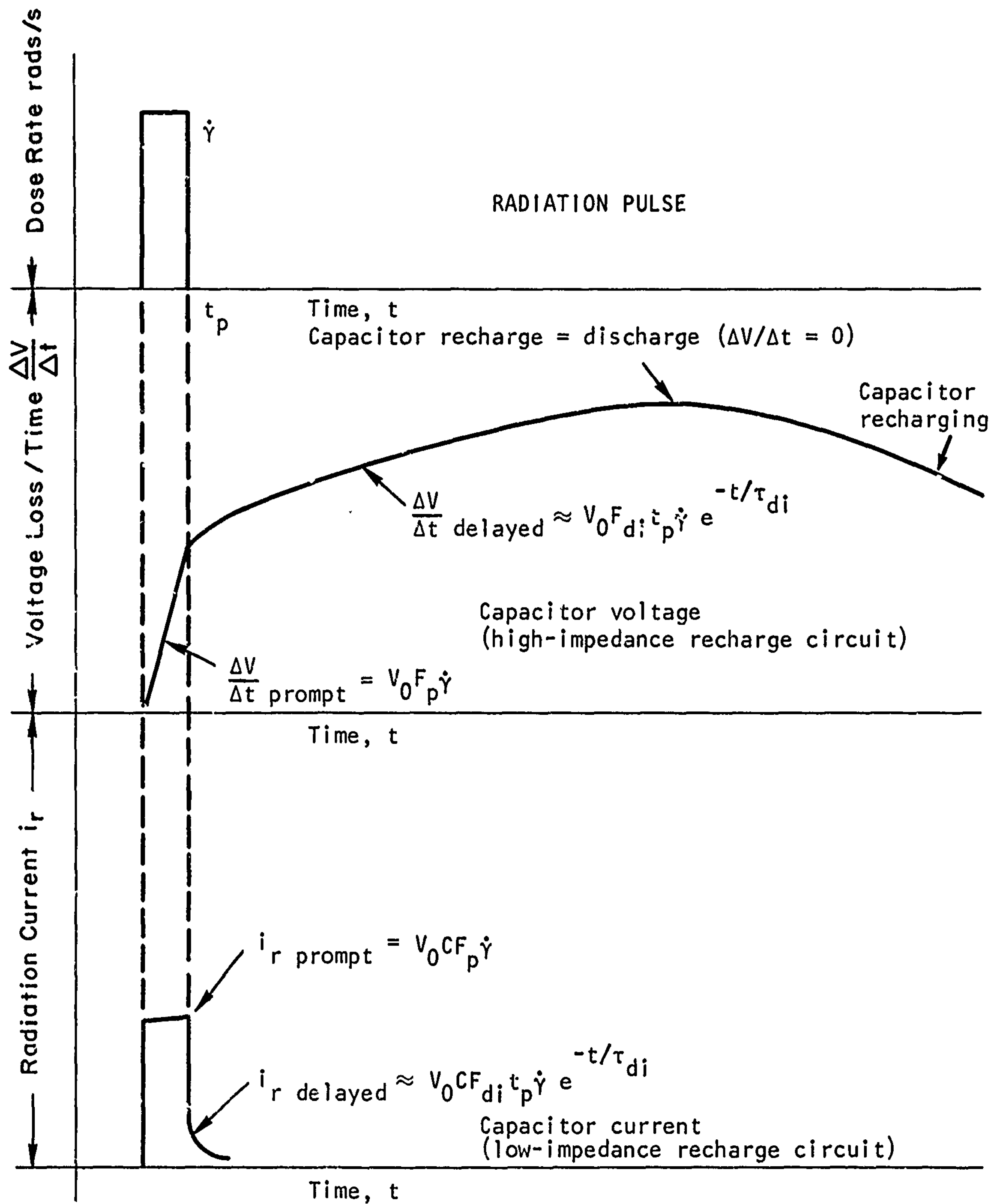

FIGURE 7.1. CAPACITOR PHOTOCONDUCTIVITY CHARACTERISTICS

Note: Combined recharging and discharging effects result in a composite voltage loss/time curve which later becomes a decreasing exponential.

The conductivity in the dielectric is given by

$$\sigma = \sigma_0 + \sigma_r \quad ,$$

where σ_0 = leakage conductivity of the dielectric and σ_r = radiation-induced conductivity. Normally, σ_0 is small enough so that it can be neglected.

The experimentally determined parameter is the current in the dielectric as a function of time, i(t), which is related to the conductivity $\sigma_r(t)$ by

$$i(t) = \frac{CV_0}{\epsilon\epsilon_0}\sigma_r(t) \quad , \tag{7.1}$$

where C is the capacitance, ϵ is the relative dielectric constant, and ϵ_0 is the permittivity of free space.

The radiation-induced conductivity can be written

$$\sigma_r = \sigma_p + \sum_i \sigma_{di} \quad , \tag{7.2}$$

where, for short-pulsed radiation,

$$\sigma_p = F_p(\gamma)\dot{\gamma} \quad , \tag{7.3}$$

$$\sigma_{di} = F_{di}(\alpha)\int_{-\infty}^{t} \dot{\gamma}(t') \exp[-(t-t')/\tau_{di}]\, dt' \quad , \tag{7.4}$$

where

$$\alpha = \gamma,\ t_p < \tau_{di};\ \alpha = \dot{\gamma}\tau_{di},\ t_p > \tau_{di} \quad . \tag{7.5}$$

In these equations,

σ_r = radiation-induced total conductivity

σ_p = prompt portion of the conductivity

σ_{di} = i^{th} delayed conductivity component

$F_p(\gamma)$ = prompt conductivity fitting parameter which may be a function of total dose

$\dot{\gamma}$ = instantaneous dose rate during the pulse

$F_{di}(\alpha)$ = fitting parameter of the ith delayed component, and a function of the dose rate times the pulse width ($\dot{\gamma} t_p = \gamma$) if the pulse width is shorter than the ith decay constant, or the dose rate times the decay time for pulse widths longer than the decay constant

τ_{di} = decay constant of the ith delayed component, which may vary during the decay.

In general, the delayed components do not decay exponentially, and the above form may not be convenient. In that case, the charge release per applied volt per unit dose per unit capacitance, called the specific charge release, is tabulated for selected time intervals, i.e.,

$$\Delta Q_{12} = \frac{1}{\gamma C}\left[\int_{t_1}^{t_2} G(t)dt\right] \quad , \tag{7.6}$$

where G(t) is the measured conductance of the capacitor.

Then the voltage across the capacitor drops by

$$\Delta V_{12} = \Delta Q_{12}\, \gamma V_0 \tag{7.7}$$

during the interval from t_1 to t_2 where V_O is the voltage on the capacitor. The average current during this time is

$$\bar{i}_{12} = \frac{\Delta Q_{12}\, \gamma C V_0}{t_2 - t_1} \quad . \tag{7.8}$$

Zero-Volt Response

At this time, the available data on the zero-volt response are incomplete and the modeling inadequate to establish a preferred parameter characterization. Zero-volt signals due to charge transfer between plates from secondary emission and differential charge scattering can be modeled by a current generator proportional to the instantaneous dose rate. This mechanism dominates in the nonelectrolytic and nonceramic capacitors where approximately 10^{-13} coulomb/(cm^2 · rad) are emitted for energetic electrons, while this number is about a factor of 5 greater for prompt fission gammas. In electrolytic capacitors, there is evidence of a built-in potential barrier which produces a photovoltaic charge release upon irradiation. The magnitude of the response decreases with accumulated dose, and total doses of 5×10^5 rads decrease the effect by about 10 percent. The peak signal is

weakly dependent on the value of the resistance shunting the capacitor (proportional to $R_L^{1/6}$ for tantalum capacitors). For short pulses, the signal is found to follow the form:

$$V = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} , \qquad (7.9)$$

where A_1 and A_2 are proportional to the dose in the pulse and the built-in voltage and vary as $R_L^{1/6}$; and τ_1 and τ_2 are independent of dose and are approximately linear in R_L.

The parameters in Equation 7.9 can be related to those in Equation 7.3 and Equation 7.4 through

$$F_{d1} = \frac{\epsilon\epsilon_O}{V_{BI}} \frac{A_1}{\gamma} \left[\frac{1}{\tau_1} - \frac{1}{RC}\right] \qquad (7.10)$$

$$F_{d2} = \frac{\epsilon\epsilon_O}{V_{BI}} \frac{A_2}{\gamma} \left[\frac{1}{RC} - \frac{1}{\tau_2}\right]$$

$$\tau_{d1} = \tau_1 , \qquad \tau_{d2} = \tau_2 ,$$

where

$$\gamma = \int_O^{t_p} \dot{\gamma} dt$$

V_{BI} = built-in voltage.

F_p is determined as described in the Data Analysis section.

Space-Charge Polarization – First Pulse Effects

The buildup and discharge of space charge in the dielectric during radiation testing are very important phenomena which can greatly affect the results of capacitor testing.

A "polarization effect" that is attributed to space-charge buildup within the dielectric material due to nonuniform trapping has been observed with most capacitors, particularly with Mylar, paper, mica, polycarbonate, and tantalum oxide devices. The effect is manifested in several ways. One of

these is an apparent decrease in the induced conductivity with sequential radiation pulsing. Charge transfer across the dielectric during a radiation pulse builds up a space-charge field opposing the applied electric field. If the applied electric field is then removed, subsequent radiation pulses result in a current in the external circuit which is opposite in direction to that observed with the field applied. This is caused by the discharge of the space-charge field. Similarly, if the electric field is reversed rather than removed after the space charge has been built up, the space-charge field enhances the applied field, and a larger current results than would be observed normally. Thus, the first pulse at a given polarity of voltage produces the largest response.

Saturation of the polarization effect, where no further decrease in the charge transfer is observed with subsequent radiation pulses, occurs after one or more pulses, depending on the capacitor and on the dose delivered in each pulse. Decreases of 50 to 70 percent for mica, 10 to 20 percent for tantalum oxide, and 30 percent for Mylar have been observed due to this space-charge buildup during radiation pulsing.

Experiments indicate that the degree of polarization depends on the total dose, but is independent of dose rate.

Models for scaling this phenomenon are not available at present, and empirical data must be generated for each capacitor type used. To examine the polarization and its effect on zero-applied-voltage signals, it is recommended that the magnitude of the polarization be determined as follows:

(1) With an applied voltage, expose the capacitor to successive radiation pulses until saturation of the polarization is achieved. Note the dose for saturation.

(2) Discharge the space-charge field (depolarize) by pulsing the radiation at zero applied volts until the normal zero-volt signal is achieved.

(3) Reapply the voltage and, with radiation pulses of 1/10 to 1/20 of the saturation dose each, measure the signal as a function of dose.

(4) When saturation is reached, remove the voltage and measure the zero-volt signal as a function of dose.

CONDUCTIVITY DATA SHOULD BE TAKEN USING THE FIRST PULSE AT A GIVEN VOLTAGE. EACH PULSE WITH THE VOLTAGE APPLIED SHOULD BE FOLLOWED BY A SUFFICIENT NUMBER OF PULSES (10 OR MORE) AT ZERO APPLIED VOLTS TO RESTORE THE DEVICE TO ITS NORMAL CONDITION BEFORE THE NEXT MEASUREMENT IS PERFORMED.

Stored charge effects which produce anomalous first-pulse responses are sometimes seen in electrolytic (e.g., tantalum) capacitors. Measurements of response of these capacitors should always include repeat measurements of the first level tested as a check for these effects.

7.3 GENERAL TEST CONSIDERATIONS

Test Specimens

The materials and/or construction of commercially available capacitors may be the primary source of uncertainty in the results obtained when these devices are irradiated. It has been found in some cases that capacitors whose measurable electrical characteristics are very nearly equal will respond very differently to a radiation pulse. Observations in this regard have included differences of as much as a factor of 5 between similar parts. Random sampling from various production lots is advisable to obtain results that will be truly representative in the basic characterization of a capacitor type.

Specimen Orientation

The orientation of the capacitor specimen is critical in LINAC and flash X-ray studies since it can influence the uniformity of dose deposition. It is generally advisable to orient the capacitor so that the beam will penetrate the specimen perpendicular to the capacitor's major axis. Consideration must be given to the range of the charged particle in the capacitor. Stopping a significant number of charged particles in the capacitor will seriously affect the results. Another consideration is that the conductivity due to highly ionizing particles may have a strong dependence on the orientation of the capacitor plates and dielectric to the incident flux.

The positioning of the test specimens for pulsed-reactor studies may not be as critical as for other studies, except for consistency, since neutron and gamma radiations are very penetrating. It is recommended, however, that the capacitor orientation be such that its major axis is perpendicular to a straight line extending through the center of the reactor core.

Temperature

Radiation effects studies for most electronic parts require the monitoring and recording of the temperature to obtain adequate data for analysis. This is especially true for capacitors since there is evidence that the radiation-induced effect is temperature dependent. Special temperature studies may even require the continuous monitoring of the temperature. Directly attaching thermistors or thermocouples to the test capacitor is the recommended method for measuring temperature. Possible degradation of the temperature sensor must be a consideration when performing these tests since it also is exposed to the radiation.

Some dielectrics, particularly ferroelectric ceramics, normally have large (nonradiation) temperature and voltage coefficients of capacitance. Since the radiation-induced current varies directly with the capacitance, it is important to consider in the data analysis the temperature and voltage changes experienced by the device during the measurements.

The recommended procedure is to determine the temperature and voltage characteristics of these devices for these test conditions prior to their irradiation.

Voltage Dependence

The voltage dependence of the radiation-induced response should be measured at each exposure level of interest. Both polarities of voltage should be applied, if possible, with the usual precautions for depolarization between each data point. Unusual behavior in the voltage dependence is a good diagnostic for "maverick" capacitors or improperly operating test circuitry.

Since the induced current is voltage dependent, care must be taken to insure that an excessive change in the voltage operating point does not occur during the radiation transient. Test circuits using sampling resistors are normally prone to this problem since a sizable radiation-induced current can cause a significant voltage drop across the sampling resistor. Even with low-impedance systems, such as current probes, problems can occur at very high dose rates or with devices exhibiting a high level of response. Voltage-stabilizing capacitors, to be used in parallel with the voltage source, should be selected to maintain the source voltage to within ± 5 percent during the radiation pulse.

Spurious Currents

Noise suppression is discussed in Section 2.5. Of particular importance to capacitor testing are those currents arising from cable currents, air ionization, and secondary emission. These sources must be eliminated or accounted for in all capacitor testing.

Supporting-Data Requirements

Adequate sample dosimetry and burst-shape indications are required. The temperature should be known to ± 2 C, and the test voltage should be measured to ± 3 percent. The capacitance of each sample should be known to ± 1 percent. The beam energy of the LINAC, the maximum energy of the flash X-ray machine, and the cutoff energy of its transmission target should also be noted. The neutron spectrum of the pulsed reactor should be known.

7.4 SOURCES

Linear Accelerators (LINAC's)

Linear accelerators are the most useful single source for dielectric characterization. Pulse widths within the nanosecond to microsecond range are obtainable, and the pulse height can be changed for each pulse width, allowing dose and dose rate to be varied independently. Other features of linear accelerators are discussed in Section 4.

Flash X-Ray Machines

These machines are described in Section 4 under "Radiation-Source Considerations".

Pulsed Reactors

Unlike gamma rays and electrons, which generate relatively isolated electron-ion pairs, neutrons, protons, and recoil atoms produce dense tracks of ionized electrons. The behavior of these ionized electrons is greatly influenced by adjacent electrons and high local fields set up by the ions.

The effects of protons from (n, p) reactions is especially important in organic dielectrics. In a reactor test, the capacitor response results from a mixed neutron-gamma field, and hence, the effects of the isolated electron-ion pairs are mixed with the effects of the highly ionizing particles.

It is recommended that these gamma effects be measured at a gamma or electron source and understood before a mixed-field characterization is attempted.

A technique, which has been used at bare critical assemblies to separate the neutron and gamma effects, is to interpose various shielding materials between the burst of radiation and the exposed component. Normally, lead and polyethylene shields are placed between the reactor and the test samples, which alters the neutron-to-gamma-ray ratio at the test samples.

In other respects, radiation-induced currents in capacitors at a pulsed reactor are consistent with the explanations given above. The pulsed reactor is useful when characterizing dielectrics known to have relatively long time constants for their delayed component. If no a priori knowledge of the dielectric is available, a simple "proof" test will be necessary.

7.5 RECOMMENDED APPROACHES

There are two recommended approaches for determining the response of charged capacitors to transient radiation. These approaches are (1) a voltage- or charge-loss technique, with the data interpretation in the terms of $\Delta V/V_0$; and (2) current measurement techniques, with the data being interpreted in terms of the photoconductivity-equation parameters.

The $\Delta V/V_0$ approach (charge loss) measures the amount of charge transferred to the plates of the capacitor as a function of time. Although the prompt current, I_p, is generally much larger than the delayed current, I_d, the prompt charge, $\approx I_p t_p$, may be of the same order as the delayed charge, $\approx I_d \tau_d$, if t_p is chosen to be much less than τ_d. Thus, for short pulses, the charge-measurement technique requires less dynamic range in the instrumentation than the current-measurement technique. The charge method is well suited for delayed-conductivity-component measurements and is recommended when the delayed charge transport is important. Care must be taken in these measurements that the voltage across the capacitor does not change by more than about 10 percent. Since spurious signals are difficult to identify by their time dependence in this technique, such signals must be carefully eliminated.

When fast-time-resolution measurements are desired or when the prompt current pulse is most significant, the current-measurement technique is recommended. Spurious signals are also more readily identified, with the fast time resolutions available with this technique. As mentioned above, the instrumentation for current measurements should have a wide dynamic range.

7.6 SPECIFIC TEST PROCEDURES

"First-pulse" effects should always be kept in mind when testing capacitors. The unbiased response should be measured for the first few irradiation pulses to check for stored charge release. Conductivity data should be taken on thoroughly depolarized capacitors; after each exposure with applied voltage, the capacitor should be pulsed with zero applied bias until the zero-volt signal is constant from pulse to pulse.

Parameter Variations

A systematic variation of the important factors is required to better insure satisfactory results when performing tests whose purpose is the basic characterization of a dielectric.

The necessity to hold relevant variables constant except the one under study is a well-understood test design requirement that avoids overcomplication of the data analysis. For example, to determine a voltage dependence, all other variables such as the dose rate incident on the component, the pulse width, and temperature are held in control to avoid confusing effects from variations occurring in one or more of these parameters with the effect of voltage.

The single-parameter-variation tests that are the most important in capacitor testing are:

(1) Dose-rate dependence. Each of several capacitors should be exposed to a wide range (preferably at least 100:1) of dose rates while the dose is held constant. This test is limited to a LINAC as the radiation source; FXR sources are not suitable, since the pulse width is fixed.

(2) Dose dependence. Each of several capacitors should be exposed to a series of pulse widths while the dose rate is held constant. This test is limited to a LINAC as the

radiation source because of the availability of variable pulse widths.

(3) Voltage dependence (to verify the direct proportionality of response current to applied voltage). This test should be performed on at least one sample of a given type.

(4) Capacitance (to verify the direct proportionality of response current to capacitance). Capacitors within a specific type or family group, covering a range of capacitance values but having the same working voltage, can be tested. With careful test structuring, this information can be obtained from the analyses of other tests.

(5) Temperature dependence. This test should be performed on several samples of dielectric types known to be temperature sensitive.

(6) Reproducibility. This test should be performed on a few individual samples under random test conditions. Some redundancy should also be included; i.e., several different samples should be measured under the same test conditions to estimate the precision of measurement and the sample-to-sample variations.

It should not be inferred that all these tests have to be performed to make a complete experiment. Perform only those tests that will satisfy the experimental objectives and, hence, satisfy the purpose of the experiment. Variation testing as described above requires a rather large matrix or sequence of measurements. Therefore, multiple-channel testing is desirable when the radiation source and economics permit.

Basic Requirements

The transient response of a capacitor due to photoconductivity is determined from measurement of capacitor voltage loss or the radiation-induced current. Analysis of the data from either measurement will produce the required photoconductivity parameters. A supplementary measurement is the replenished charge which is the integral of the radiation-induced current.

Radiation-induced current transients are monitored by two methods: measuring the voltage drop across a sampling resistor in series with the device and measuring the output of a current transformer (current probe) used in the circuit. Capacitor-voltage-loss transients are monitored by measuring the voltage across the test device.

Adequate data for interpretation of the results of transient-effects measurements cannot be overly stressed. The following are the basic requirements for data obtained during irradiation.

- Identification of all test equipment
- Accuracy of all test equipment
- Radiation pulse shape (LINAC and flash X-ray)
- Instrument scale factors
- Capacitor orientation with respect to the beam or reactor core
- Exact circuit configuration, included grounding scheme

Specific parameter requirements concerning a measurement are included in the section on that measurement.

Capacitor-Voltage-Loss Measurements

Figure 7.2 is the recommended circuit for measuring capacitor voltage loss, ΔV, during exposure to transient radiation. Use of this circuit and/or measurement should be limited to experiments involving radiation-pulse widths and intensities (i.e., dose/pulse) such that the capacitor voltage loss does not introduce significant error in the analysis ($\Delta V \leq 10$ percent). The limiting factor in the analysis is that a constant applied voltage is assumed.

The circuit components of Figure 7.2 are defined as follows:

- V_0 is the bias voltage
- R_1 is the value of the load resistance
- C_2 is the power supply cable bypass. It must be large enough to supply the transient current and remain a stiff voltage source during the radiation transient. The time constant $2R_2C_2$ should be larger than any time constant of interest.

The voltage-measurement circuit is essentially an "open" circuit technique and requires that the capacitor recharge time constant be long, i.e., $R_1C_1 >> \tau_d$. This means that after one circuit time constant, R_1C_1, the capacitor voltage change should still be greater than two thirds of the peak response. If this is not the case, the resistance value of R_1 should be increased to meet this circuit requirement. Note that since R_1 is in the

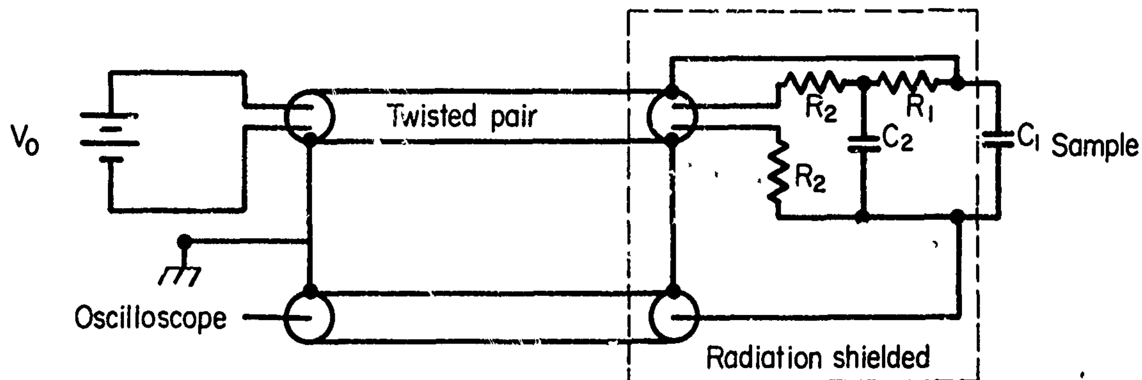

FIGURE 7.2 VOLTAGE-MEASUREMENT CIRCUIT

ground leg of the circuit, the oscilloscope system can be dc-coupled and R_1 can be made as large as necessary.

Data to be recorded in addition to those listed in the immediately preceding "Basic Requirements" paragraph shall include:

- R_1
- Applied voltage, V_0
- ΔV versus time
- Ambient temperature.

Sampling Resistor Technique for Short-Pulse Measurements

Figure 7.3 is the recommended circuit for measuring radiation-induced current by the resistor method. This circuit is used when maximum sensitivity is required or when the time duration of the transient current exceeds the pulse-width capability of current probes.

The circuit components of Figure 7.3 are defined as follows:

- R_0 is equal to the cable characteristic impedance.
- C_2 is the power supply cable bypass. It must be large enough to supply the transient current and remain a stiff voltage source during the radiation transient. The time constant $2R_2C_2$ should be larger than any time constant of interest.

- R_1 – The value of R_1 is selected to satisfy one of the following conditions:

  (1) For best pulse response, R_1 should equal R_O.

  (2) For maximum sensitivity, R_1 may be omitted.

  (3) When operating, point deviations must be held to a minimum and sensitivity is not critical; R_1 may be very small. Note that the conductivity current-induced voltage across the resistors R_1 equals the change in voltage across the test capacitor and should be kept to 1 percent or less of the applied voltage.

If a good radiation-insensitive amplifier system is available, its insertion in the signal-measuring cables near the sample allows the option of increasing R_1 for enhanced sensitivity or desired integration.

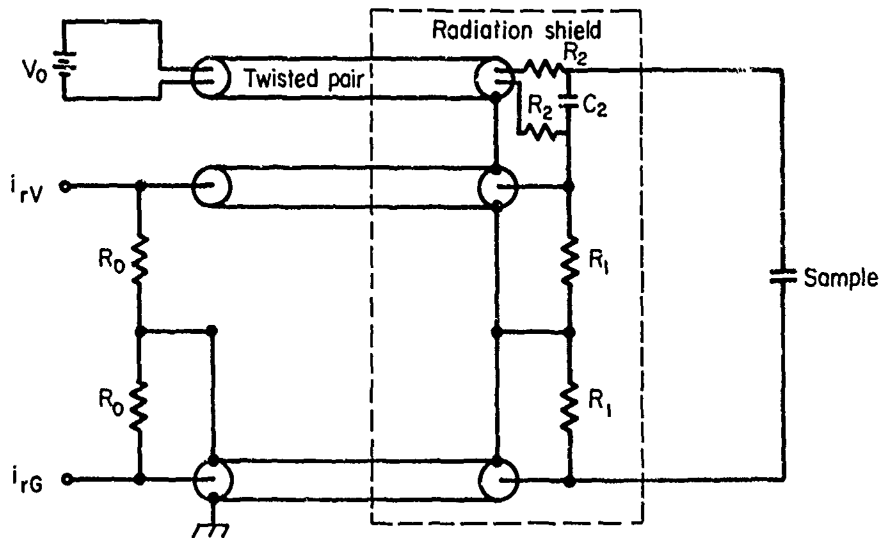

FIGURE 7.3. CURRENT MEASUREMENT CIRCUIT USING SAMPLING RESISTOR

Data to be recorded in addition to those listed in the preceding "Basic Requirements" paragraph shall include:

- R_1 and R_0
- i_r versus time
- Ambient temperature
- Applied voltage, V_0.

This circuit does eliminate noise in the output cables and the spurious signal due to the symmetric component of the charge emission. It does not eliminate any unsymmetric component to the charge emission. In some installations, the low side of the capacitor can be grounded, and the ground signal cable eliminated.

Current-Probe Sampling

Figure 7.4 is the recommended circuit for measuring the radiation-induced current by the current-probe method. This circuit is used when minimum deviation of the operating point is required.

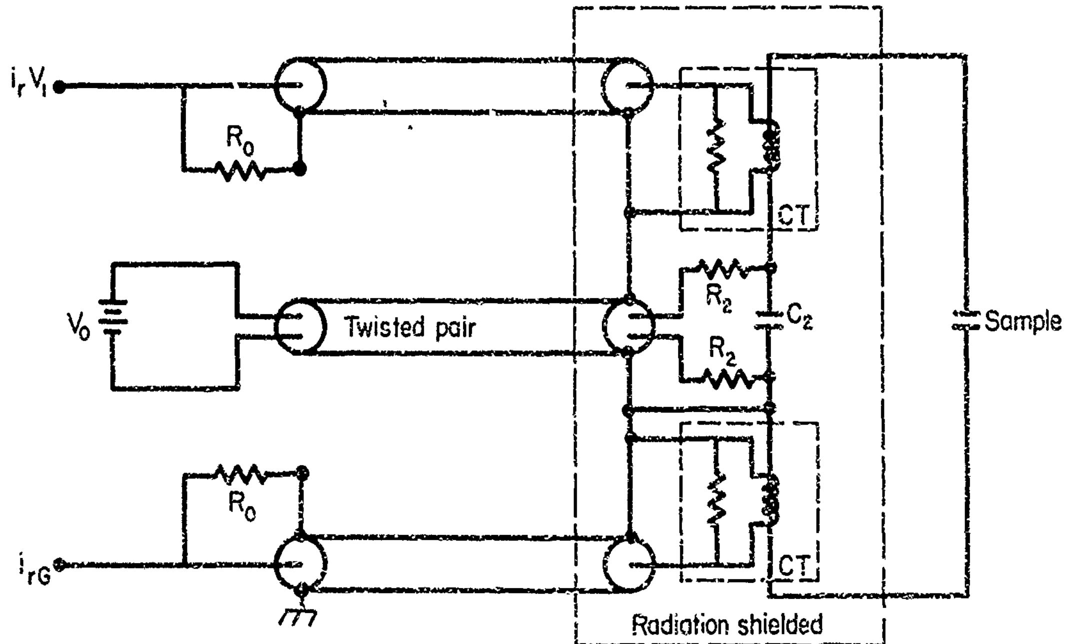

FIGURE 7.4. CURRENT MEASUREMENT CIRCUIT USING CURRENT TRANSFORMERS

The circuit components of Figure 7.4 are defined as follows:

- R_0 is equal to the cable characteristic impedance, which should be chosen to match the current probe.
- C_2 is the power supply cable bypass. It must be large enough to supply the transient current and remain a stiff voltage source during the radiation transient. The time constant $2R_2C_2$ should be larger than any other time constant of interest.
- CT is a current transformer with suitable response.

A series resistance may be required to eliminate oscillations in this circuit when performing some measurements. A compromise between desired high-speed response and the reduction of oscillation must be sought with this circuit.

Data to be recorded in addition to those listed in the preceding "Basic Requirements" paragraph shall include:

- R_0
- Identification of the current transformer
- i_r versus time
- Ambient temperature
- Applied voltage, V_0.

This circuit is usually not suited for longer term delayed component measurements.

Replenished-Charge Measurement

The most commonly used technique for determining replenishment charge is the measurement of capacitor voltage loss in a long-time constant circuit (see preceding "Capacitor Voltage Loss Measurements" paragraph). This technique covers a very large dynamic range in current and time. Other methods of determining this parameter, which is the integral of the radiation-induced current, are by manually extracting the information from a photograph of the current display or by electronically integrating the current signal as shown in Figure 7.5.

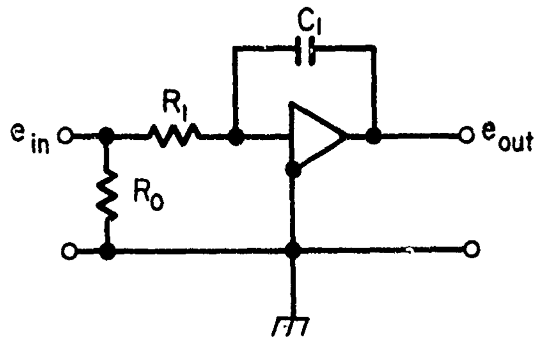

FIGURE 7.5. CHARGE-INTEGRATION MEASUREMENT CIRCUIT

The required period of integration can be determined experimentally by integrating a known current. The time constant of the integrator, determined by R_1 and C_1, must be very long when compared with the period of integration in order to have a negligible loss of charge during the period of integration. Charge is determined from the following relation:

$$\int V_{in} dt = V_{out}(R_1 C_1) \quad . \tag{7.11}$$

Direct Measurement of i_r for Pulsed-Reactor Tests

Differentiation of the current through the sampling resistor (V_R/R_1) yields a direct indication of i_r as a function of time. Figure 7.6 is the recommended differentiation circuit.

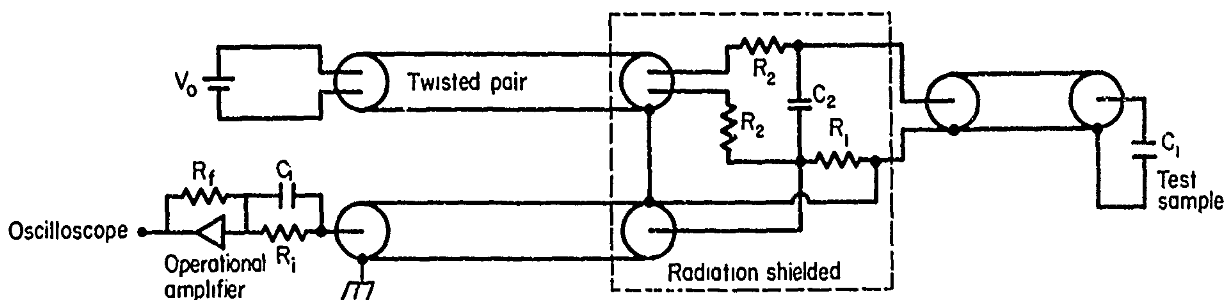

FIGURE 7.6. CIRCUIT FOR DIRECT MEASUREMENT OF i_r, LONG PULSES

The circuit components of Figure 7.6 are defined as follows.

- R_i and C_i are chosen so their product closely approximates the circuit time constant T.
- R_f and C_i are chosen so R_fC_i is small enough that the differentiation is performed with sufficient accuracy.
- C_2 is the power supply cable bypass. It must be large enough to supply the transient current and remain a stiff voltage source during the radiation transient. The time constant $2R_2C_2$ should be larger than any time constant of interest.

Data to be recorded in addition to those listed in the preceding "Basic Requirements" paragraph shall include:

- R_i, C_i, R_f
- di/dt
- Ambient temperature
- Applied voltage, V_0.

The operational amplifier is used as a differentiator on one oscilloscope channel to measure di/dt, while another channel uses a conventional preamplifier to record voltage. The induced current, i_r, is then determined from

$$i(t) = i_r(t) + R_1C_1 \frac{di}{dt} \quad . \tag{7.12}$$

A background test should be performed, prior to the testing of capacitors, to determine if the noise level that may be associated with the analog differentiation of this circuit is excessive.

As an aid to accurate analysis of the transient effects data, a time-mark generator should be used to determine accurately the time correlation between the radiation burst and component behavior in this method of measurement. Timing marks should be superimposed on all oscilloscope traces taken during a particular reactor pulse. In addition, one timing mark should be placed between two others near the center of the trace to act as a master time mark. This method allows for the absolute determination of simultaneity among the oscilloscope traces taken during a single reactor pulse.

7.7 DATA ANALYSIS

A variety of analytical methods have been used to extract critical characterizing parameters from the response of common dielectric capacitors to the transient radiation environment. The defining parameters unfolded by these methods may differ somewhat, but the techniques of converting one to the other are clear-cut.

The merits of the following analytical methods are that they are relatively straightforward in concept and application. They are basically applicable to all radiation sources, with the exception that any analysis with capacitor voltage loss data, $\Delta V/V_0$, should be limited to short radiation pulses (LINAC and flash X-ray). Although other methods may be appropriate for data analyses, deviations from these preferred procedures must be justified.

Determination of F_p

For a short square radiation pulse ($t_p << \tau_d$), F_p can be determined from capacitor voltage loss or radiation-induced current data through the following relationship:

$$\frac{1}{V_0}\frac{dV}{dt} = F_p \dot{\gamma} = i_r/CV_0 \quad , \qquad (7.13)$$

where

$\frac{dV}{dt}$ = slope during pulse (see Figure 7.1)

V_0 = applied voltage.

Determination of F_d From Voltage-Loss Data

Analysis involving more than one delayed component of conductivity requires curve fitting for separation of the components in the observed composite decay. However, it is estimated that for 95 percent of circuit analysis problems, a single exponential function describing the delayed photoconductivity is adequate.

Therefore, assuming a single delayed component, σ_d, and short pulses ($t_p << \tau_d$) of constant dose rate,

$$\sigma_d \approx F_d \dot{\gamma} t_p e^{-t/\tau_d} \quad . \qquad t > t_p \quad . \tag{7.14}$$

For a short time following the pulse,

$$F_d = \frac{1}{V_0 \dot{\gamma} t_p} \frac{\Delta V}{\Delta t} \quad , \tag{7.15}$$

where $\Delta V/\Delta t$ is the constant slope of the observed curve immediately following the pulse.

Determination of Decay-Time Constant From Voltage-Loss Data

The high resistance (R_1) in series with the battery in the capacitor voltage-loss circuit, Figure 7.2, restricts the flow of recharging current to the capacitor. Thus, current flow due to the delayed conductivity immediately following the radiation pulse is essentially from the capacitor storage.

$$i_0 = C_1 \frac{\Delta V}{\Delta t} \quad . \qquad t_p < t << \tau_d \quad . \tag{7.16}$$

At the time of maximum response, t_m, the capacitor recharge and discharge currents are equal and $\Delta V/\Delta t = 0$ (Figure 7.1). The current, $i(t_m)$, is obtained by dividing the maximum voltage at this instant in time by the series resistance, R_1. The decay time constant, τ_d, is determined from these parameters through the following relationship:

$$\tau_d = \frac{t_m}{\ell n \left(\frac{i_0}{i(t_m)} \right)} \quad . \tag{7.17}$$

Parameter Determination From Radiation-Induced-Current Data for Short Pulses ($t_p << \tau_{di}$) of Constant Dose Rate

The radiation-induced current is

$$i_r = \epsilon\epsilon_0 C_1 V_0 \left[F_p \dot{\gamma} + \sum_i F_{di} \gamma e^{-(t-t_p)/\tau_{di}} \right] , \quad (7.18)$$

where γ is the dose in the pulse and $t = 0$ corresponds to the beginning of the pulse. For $t = t_p$,

$$F_p = i_r / \epsilon\epsilon_0 C_1 V_0 \dot{\gamma} \quad . \quad (7.19)$$

The prompt component can then be subtracted from the signal, and F_{di} and τ_{di} unfolded by standard graphical techniques.

Special Considerations for Electrolytic Capacitors

The built-in voltage, V_{BI}, modifies the response of electrolytic capacitors, and some special considerations apply.

The value of V_{BI} can be determined by irradiating the capacitors at a low dose rate (e.g., with a Co^{60} source) with one end grounded and the other end connected to a high-impedance voltmeter ($\sim 10^{11}\,\Omega$ to ground). The voltage across the capacitor will rise to a saturation value approximately equal to V_{BI}.

The recommended circuit is shown in Figure 7.3 where $R_1 C >> t_p$. Then the data can be readily fitted to Equation 7.9.

The parameter F_p can be calculated from

$$\frac{1}{V_0 + V_{BI}} \frac{dV}{dt} = F_p \dot{\gamma} \quad . \quad (7.20)$$

To determine the conductivity parameters for an applied voltage from fitting Equation 7.9, simply replace V_{BI} in Equation 7.10 by $V_0 + V_{BI}$. Note that since V_{BI} is less than a few volts, it can be neglected for large values of V_0.

Special Considerations in the Analysis of Data From Flash X-Ray Studies

The burst shape at a flash X-ray cannot be described well in closed form (mathematically). This means that the analysis must be based on (1) approximate descriptions of the burst shape or (2) computer-aided numerical techniques.

The most common technique is to assume that the flash X-ray pulse is adequately represented by a square wave that has a pulse width equal to the flash X-ray pulse width at half-maximum amplitude. The effective dose rate for the square wave is determined from the dose delivered in the flash X-ray pulse.

A more satisfactory technique, however, is to use a computer and a curve-fitting technique. A numerical description of the actual flash X-ray burst shape is applied to Equation 7.16 using estimated values for the conductivity parameters. The resulting radiation-induced current as a function of time is then applied to the measurement circuit equation - usually Equation 7.10 - to obtain a prediction of the circuit current as a function of time. After comparing the predicted and measured responses, refinements can be made in the estimated values of the conductivity parameters. Successive passes with this procedure will lead to an accurate determination of the desired parameters. This iterative technique is expensive and time consuming, but probably most accurate. It is important, however, that the response measurements be relatively free from spurious current effects, but this is true for any analytical method.

Special Considerations in Analysis of Data From Pulsed Reactor Studies

The general characteristics of the radiation-induced conductivity will be discussed in terms of the induced current, i_r. During the initial rise of the radiation pulse, i_r is proportional to the dose rate, $\dot{\gamma}$, modified by the dose dependence of F_p. If the F_p is a constant in this time interval, a semilog plot of i_r and $\dot{\gamma}$ versus time will indicate the same period for both quantities, provided they are actually proportional. They would be proportional for this interval since the dose rate, $\dot{\gamma}$, is rising exponentially. The function F_p can be determined from LINAC data if it is not constant. For an exponentially rising burst shape, a semilog plot of i_r and $\dot{\gamma}$ versus time is shown in Figure 7.7, where F_p = constant and indicates equal periods for the initial rise.

The induced current is not proportional to $\dot{\gamma}$ at the later times in the burst; it does not decrease as rapidly as the dose rate (Figure 7.7). The magnitude of the current at the start of the decay is much larger than the current that can be induced by the residual radiation existing at this time. It would be expected that the current would decay exponentially with a time constant equivalent to the circuit time constant; however, it is evident from the figure that i_r maintains a value that is disproportionately large compared with that during the major portion of the burst. This is clearly indicative of a delayed component in i_r. This delayed component, τ_d, is then determined from the slope of this semilog plot over the chosen measurement time interval.

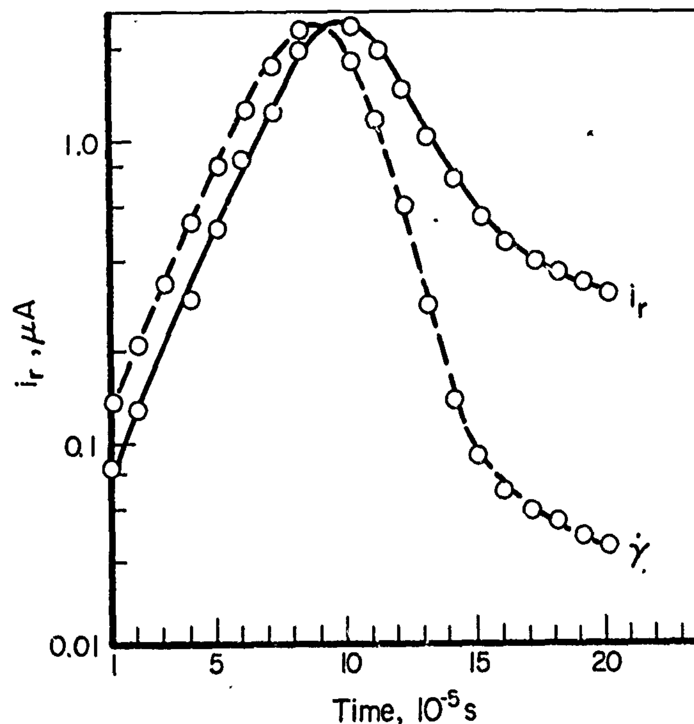

FIGURE 7.7. SAMPLE i_r AND $\dot{\gamma}$ DURING A PULSED REACTOR BURST

7.8 DATA REPORTING

If the test was conducted as a simple proof test, the test circuit and temperature during irradiation should be given along with the beam energy and pulse width of the machine. A reproduction of the pulse shape is desirable. Any procedures used to reduce spurious currents should be described

in detail. For each sample, the applied voltage, capacitance, working voltage, dose rate, and dose [in rads (dosimeter)] are required along with the maximum circuit current achieved. The bias history of the capacitor should also be reported. It is recognized that proof-test data are generally of little value to anyone other than the user, but by reporting the data in this way, their usefulness and validity can be better assessed.

For basic dielectric-characterization tests, the method of analysis should be described. In addition to the information given above, the following information is also required for each sample: The derived values of F_p and F_{di} and the delay times τ_{di} should be given. The circuit time constant should be given if it is not readily apparent from the test circuit description. The results of any redundant or repeated measurements should be given. If five or more similar samples were irradiated at the same test condition, the average values of F_p, F_{di}, and τ_{di} should be reported. Clear statements should be given as to any inferences obtained from the data concerning dependences on voltage, dose rate, capacitance, pulse width, or temperature. Tables 7.1, 7.2, and 7.3 show standardized formats for presenting these data. Graphs showing the radiation-induced current versus these parameters (and a least-squares fit to the data) are very desirable. Graphs should complement tabulated data, not replace it.

If measurements were made to determine the relative neutron ionization effectiveness, the shield arrangements and the neutron-to-gamma ratios obtained should be presented, along with any neutron-spectrum measurement results. For each sample, the neutron fluxes, the proportionality constant F, and the ratio of the neutron-induced current to the total current should be given.

TABLE 7.1 GENERAL INFORMATION

Date of test ____________________

Test facility ____________________

Diagram of capacitor orientation:

Dosimetry method

Measurement technique ____________________

(Draw circuit below, including power supply and grounding scheme)

Additional Comments:

TABLE 7.2. PARTS TABULATION

Serial No.	Rated Capacitance, μF	Tolerance, ± %	Working Voltage	Case Size	Manufacturer	Measured Capacitance 1 kc, μF	Date of Manufacture	Date of Purchase	Unit Designation in Test

TABLE 7.3. CAPACITOR IONIZATION-EFFECTS DATA

Date ______________

Unit Designation	V, ± volts	Dose Rate, rads (Si)/s	Dose, rads (Si)	Pulse Width, μs	T, C	$F_p/\epsilon\epsilon_0$, rad^{-1}	F_{d1}, $\frac{\Omega\text{-cm}}{rad}$	τ_1, μs	F_{d2}, $\frac{\Omega\text{-cm}}{rad}$	τ_2, ms	Etc.

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8.0 MICROCIRCUITS

8.1 SCOPE

This section deals with experimental procedures for determining the response of microcircuits to the nuclear-weapon environment. The approach of this Section is to group the microcircuits into two general classes - digital and linear circuits - although some interface circuits do not fall clearly into either class. With these two classes some additional distinctions are made as to the circuit function, design, and construction. Each microcircuit type is designed to function in a very specific way to perform a very specific task. The tests for the microcircuit should be designed to evaluate its capability of performing that task. Since this Section could not possibly cover all possible combinations of microcircuits and parameters to be measured, it will be necessary for the reader to develop from the material presented the specific tests necessary to characterize a particular microcircuit type. In correctly developing a test plan for these devices it is important that the reader not only utilize the examples and guidelines presented in this Section but also utilize the information in Section G of the TREE Handbook, Volume I, to estimate the gross response of the microcircuit.

8.2 PERMANENT-DEGRADATION MEASUREMENTS

Neutron Damage in Microcircuits

Neutron interactions with silicon result in a reduction of the minority carrier lifetime causing a reduction of bipolar transistor gain, an increase in junction leakage currents, and a shift in junction voltages. A secondary effect, important at large neutron fluences, is carrier removal, which causes an increase in diode and transistor bulk resistances, a decrease in transistor gain at high currents, an increase in transistor saturation voltage, and changes in the equilibrium carrier concentration in majority carrier devices. The most significant of these changes is the degradation of transistor gain. Typically, the observed degradation in microcircuit performance such as loss of fanout capability, loss of circuit gain, increased offset current, or changes in input biasing reflects primarily the loss in gain of the circuit transistors. Furthermore, the microcircuit parameters just mentioned and the device's switching characteristics are sensitive to the rapid annealing phenomena (see annealing discussion in Section G of the TREE Handbook DNA-H 1420.

Total Ionizing Dose Damage in Microcircuits

Large doses of ionizing radiation cause a positive space charge to accumulate within the oxide passivation layer and can cause an increase in the density of interface states. These phenomena affect bipolar transistor gain, junction leakage currents, junction breakdown voltages, and threshold voltages for MOSFET and thin-film devices. Unlike those for neutron damage, total dose effects are sensitive to bias conditions during irradiation. In addition, some annealing of total ionizing dose damage does occur.

Total ionizing dose effects on MOS and thin-film transistor digital-circuits results from a shift of the gate turn-on or threshold voltage of the transistors. The primary circuit response is a shift in the input threshold voltage and output voltage levels. The failure level for these circuits depends strongly on the circuit design and the manufacturing process.

The effect of total ionizing dose on linear circuits ultimately results in changes of input offset voltage, input impedance and input bias current.

Parameters to be Measured

Since the output response of digital circuits is generally a nonlinear function of gain degradation and threshold voltage shifts, it is desirable to observe electrical parameters that indicate the "gain" and "noise" margins of a particular unit. The electrical parameters most indicative of gain and noise margins are the impedance characteristics of the input and output terminals and the transfer characteristic between input and output. The impedance characteristics are useful since they tend to show circuit changes occuring before those changes significantly affect specified circuit operation. Input and output impedance characteristics should be measured for both logic states and should cover all possible loading configurations for the particular application under consideration. Typically the impedance and transfer characteristic measurements result in a set of oscilloscope traces or X-Y plots that are not necessarily convenient to record or compare. Alternatively, a set of discrete points that contain the essential information of these characteristics may be obtained from these curves or may be measured individually, thus making recording and comparison easier. The discrete points that are generally characterized include:

- Input current, high level
- Input current, low level
- Input voltage, high level (minimum value)
- Input voltage, low level (maximum value)

- Output short circuit current
- Output voltage, high level (minimum value)
- Output voltage, low level (maximum value).

The number of parameters measured and the operating conditions during measurement and irradiation will be determined by the data requirements of the experiment. Table 8.1 summarizes the operating configurations for the various digital circuit "black-box" tests usually of interest to the system designer for the assessment of neutron fluence and total dose effects on digital microcircuits. The effects of neutrons on microcircuit switching performance can be analyzed by assuming that the switching speed is composed of two parts: (1) an "intrinsic" switching speed for the basic circuit with a negligible load capacitance and (2) a capacitive charge-discharge time to drive the output load. Usually the intrinsic switching speed will change only slightly with neutron degradation because the switching times are weakly dependent upon internal transistor gains. The output capacitance charge-discharge time depends strongly upon the ability of the circuit to act as a sink, and hence is strongly dependent upon transistor gain. As a result, switching time measurements are best accomplished using the standard fanin-fanout configuration recommended by MIL-STD-883.

As for digital circuits in a neutron environment, the primary causes of linear-microcircuit failure is transistor-gain degradation. The degradation of a linear circuit's performance is characterized by radiation-induced changes in the transfer characteristics. For linear circuits the more significant changes occur in the circuit gain, the input bias current, and the input offset current and voltage. The circuit gain in general will degrade less than the transistor gain, depending on the degree of feedback in the circuit. The input bias current is usually inversely proportional to the gain of the input transistor because most input stages are biased at constant emitter current [$I_{BIAS} \sim I_E$ (Const)/h_{FE}]. The input offset current of a circuit with a differential input is inversely proportional to the differences in gain of the input transistors. Changes in offset voltages are the result of shifts in junction voltages and changes in bulk resistivity.

A somewhat different situation occurs with low level switches that use transistors as choppers. The collector-emitter voltage in the normal connection is proportional to $1/\beta_I$, and the collector-emitter voltage in the inverted connection is proportional to $1/\beta_N$. Since $\beta_N > \beta_I$, the offset voltage change is primarily because of β_I.

Parameters which are less affected by neutrons but still change significantly are the circuit frequency response, slew rate, output dynamic range and noise figure.

In addition to neutron effects, linear microcircuits are sensitive to total dose effects. Since the input transistors of most microcircuit amplifiers operate at very low current levels, these transistors are particularly

TABLE 8.1 DIGITAL CIRCUIT PARAMETERS AND TYPICAL MEASUREMENT CONFIGURATIONS

Parameter	Typical Measurement Configuration (All Supply Voltages are Worst Case)
Input Impedance	Output(s) floating All other inputs are worst case
Input Currents, Low Level	Worst-case low level input voltages Outputs float All inputs tested individually[(a)]
Input Current, High Level	Worst-case high level input voltages Outputs float All inputs tested individually[(a)]
Low level input voltage	Worst-case load on output Unused inputs tied to worst-case voltage Measure the low level input which achieves worst-case output voltage
High level input voltage	Worst-case load on output Unused inputs tied to worst-case voltage Measure the high level input voltage which achieves worst-case output voltage
Output Impedance ("1" State)	Untested outputs float Input terminals worst-case for a "1" output on tested terminal
Output Impedance ("0" State)	Untested outputs float Input terminals worst-case for a "0" output on tested terminal
Output Short Circuit Current	Inputs adjusted to provide "high" output level Output terminal forced to ground potential
Low Level Output voltage	Worst-case input levels to provide maximum low output level Force current equal to worst-case low level fanout from test level
High Level Output Voltage	Worst-case input levels to provide a minimum high level output Force current equal to worst-case high level fanout from tested terminal
Switching Time	Untested outputs float Worst-case fanin and fanout with like or appropriate circuit(s) Unused inputs tied to appropriate potential
Propagation Delay	Untested outputs float Worst-case fanin and fanout with like or appropriate circuit(s) Unused input tied to appropriate potential

(a) May be relaxed to sampling an input after a statistically significant number of measurements show that a sample measurement would be sufficient.

sensitive to surface effects resulting from ionizing radiation. Parameters usually affected include input current, input impedance, input offset current, and open-loop gain.

JFET input stages are not subject to significant gain degradation, but other parameters, such as offset voltage and leakage current, may change significantly.

In general, a large variety of test configurations are available for linear circuits. The configuration used should be dictated by the objective of the study being conducted. Repeatable circuit operating conditions and biasing should be set for the pretest measurements. With linear circuits in particular, it may be difficult to maintain the same conditions for measurement during and after exposure because of the changing circuit characteristics due to the radiation. As an example, general circuit gain measurements on linear circuits should be made with an open-loop configuration where possible. If stable measurements in the open-loop configuration are marginal it may not be possible after exposure to repeat it. In that case, closed-loop configuration with a minimum feedback should be used.

Annealing

The observed annealing in microcircuits may be quite different from that found in simple discrete devices due to changing internal operating conditions. However, most of the rapid annealing of microcircuits is due to the rapid annealing of their bipolar transistors. Typically, rapid annealing is observed in digital circuits as a change in propagation delay and a change in source and sink current. For linear amplifiers, rapid annealing affects the circuit gain and bias current.

In addition to rapid annealing, the radiation-induced parameter changes in microcircuits exhibit some degree of long-term annealing as a result of room-temperature storage and continued operation. This room-temperature annealing is particularly important when characterizing surface effects. For this reason it is important that a record be maintained of the time and the bias conditions between irradiation and measurement.

Temperature

The electrical performance of microcircuits can be significantly affected by temperature. For example, in digital circuits the lower the temperature the smaller the gain margin and the less neutron degradation the circuit will be able to tolerate. Typically, microcircuit temperature responses are larger than the changes due to thermal annealing and/or the difference due to the temperature dependence of the neutron damage. Therefore, it is possible to irradiate microcircuits at a fixed temperature, such as

room temperature, and to later measure their responses over the specific temperature range of operation. However, when observing rapid annealing, the annealing factor is a strong function of irradiation temperature. Therefore, separate sets of data should be taken for rapid annealing of circuit response at each ambient temperature of interest.

Test Considerations

General test considerations for measurement of microcircuit parameters are discussed here. Several basic considerations and test-design decisions, which are not related specifically to the measurement of a particular parameter, must be made when planning for a microcircuit radiation test. A discussion of these test considerations is given in Section 2.5.

Data that should be taken on all tests are enumerated here. They are not repeated in the descriptions of specific test procedures. It is recommended that the following data be recorded in any pre/posttest or series of tests:

(1) Neutron fluence, neutron energy spectrum, and gamma dose (or gamma dose rate) in the locale of each group of samples for each irradiation

(2) The irradiation time period and the time period between irradiation and measurement

(3) Ambient temperature during irradiation and measurement

(4) Bias conditions from time of pretest through posttest. Record whether power is interrupted for making measurements

(5) The accuracy and precision of the measurement expected.

For *in situ* tests special attention should be placed upon recording:

(1) Time history of the radiation rates

(2) Time history of the irradiation-chamber temperature.

Certain portions of the exemplary circuit configurations are assumed to be isolated from the radiation environment. Such isolation is either indicated by cabling (for *in situ* tests) or is simply understood (for pre/posttests). Care should be taken to assure the existence of this isolation. Information on the requirements for data reporting is given in Section 8.4, Data Reporting.

When irradiating circuits under bias it is desirable to operate them in a typical manner particularly in light of their expected operating frequency as compared to the tactical pulse width and the pulse width of the simulation

facility. Circuits whose operation is static during exposure may operate differently after irradiation than if they were operated continuously throughout the exposure. An example of such an effect would be a digital gate left in a state in which the output transistor was turned off. Upon the resumption of continuous operation, the rapid annealing begun by the output transistor would cause circuit operation to change during the first second. Another example would be a flip-flop left in a single state during irradiation. Because of unsymmetric bias conditions, its degradation may be unsymmetric and a preferred state or unsymmetric characteristics might result. The possibility of unsymmetric output characteristics makes it wise to consider characterizing both states of both outputs of flip-flop type circuits.

For tests performed in situ, the experimenter must be aware of the loading which long test cables will have on the circuit under test.

Specific Digital Circuit Test Procedures

Impedance Measurements

A useful technique for observing the permanent degradation of digital circuits is the measurement of the I-V characteristics of the input and output terminals. These measurements that show the dynamic impedance of the circuit terminals can be conveniently taken with a transistor curve tracer. An X-Y plotter also can be used although the plotter requires a suitable swept low-frequency power source. Figure 8.1 shows recommended techniques for making these measurements.

The curve-tracer technique is easily instrumented and can be applied within the operational capabilities of the curve tracer. In addition to the information required in "Test Considerations" one should

- Describe curve tracer
- Make a permanent record of the trace by taking a picture
- Record all the curve tracer settings.

In utilizing the X-Y recorder method, the sampling resistor has to be of such a magnitude as to apply an almost full scale voltage to the Y channel input for the current expected. The value of the resistor should be known within 1 percent. The power amplifier must be capable of sourcing or sinking the required current at the extremes of the I-V curve. The sweep output from an oscilloscope can be used with a diode clamp to provide the ramp function. In addition to the information requested in "Test Considerations" one should

- Describe the test equipment used
- Record sampling resistor value with its tolerance
- Permanently record the trace and record the scale for each axis.

Examples of the application of this tehcnique to varoius types of digital circuits are discussed below.

The output impedance curve of a TTL circuit in the 0 state as shown in Figure 8.2 has a knee at high currents because the output transistor comes out of saturation. Because the base current of the output transistor depends primarily upon resistor values and the power supply voltage, the base drive remains nominally constant as the gain changes, and the drop of the knee of the impedance curve with neutron fluence is proportional to the change in the output transistor gain. The difference between the current at the knee and the worst-case sink current required at maximum fanout is the gain margin. Requiring a significant gain margin for all circuits ensures that a relatively large change in component transistor gain will be required to cause failure after neutron irradiation. Impedance curves can also be made at the input terminal of the TTL circuit and at the output for the 1 state. However, neither of these curves is as useful as the 0 state output curve.

The same measurements can be used for DTL circuits, because they are functionally identical to TTL circuits and must also accept current from loading circuits when the output is in the 0 state. The impedance technique can also be applied to RTL circuits. The low noise margin of RTL circuits makes the input impedance characteristic almost as important as that of the low-level output impedance.

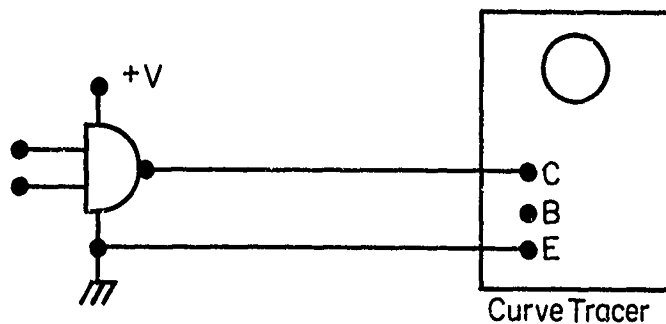
Emitter-coupled logic circuits are nonsaturating circuits whose circuit operation is similar to that of a differential amplifier in that the significant dc parameter is the input current required for operation. This can be measured with either the impedance curve at the input terminal or by a conventional dc method (MIL-STD-883).

It is also possible to obtain selected points on the impedance curves with other individual test setups such as an integrated circuit tester; this technique may be more convenient when large numbers of circuits are involved. The parameters of most interest are listed in Table 8.2 along with the recommended military standard test method.

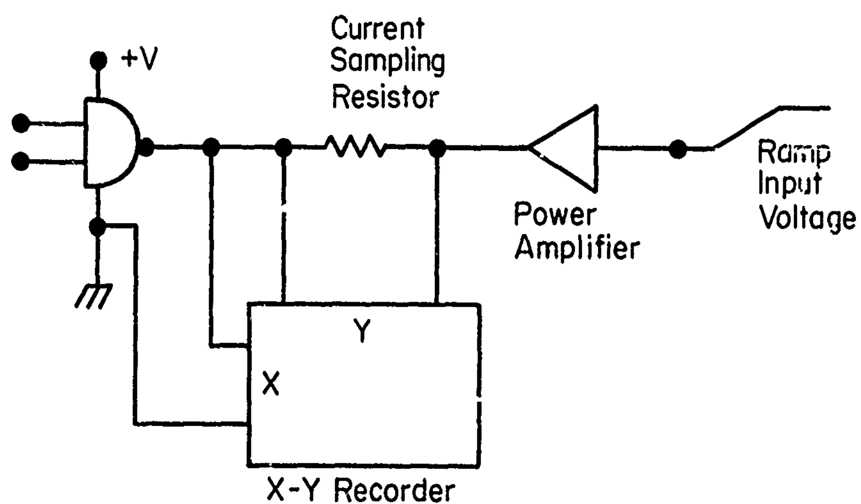
TABLE 8.2 DISCRETE INPUT-OUTPUT PARAMETER MEASUREMENTS FOR DIGITAL CIRCUITS

Parameter	Method from MIL-STD-883
High Level Output Voltage, V_{OH} (Minimum Value)	3006
Low Level Output Voltage, V_{OL} (Maximum Value)	3007
Output Short Circuit Current	3011
High Level Input Voltage, V_{IH} (Minimum Value)	(a)
Low Level Input Voltage, V_{IL} (Maximum Value)	(a)
Input Current, Low Level	3009
Input Current, High Level	3010
Low Level Output Current, I_{OL} (Minimum Value)	(b)

(a) Use test method 3006 or 3007 depending on type of circuit. That is, for an inverting gate, the high-level input test would use the low-level output voltage method (3007) while for a noninverting gate the high-level input test would use the high-level output voltage method (3006). The additional procedure added to the methods is that: Appropriate voltage-measuring equipment is used to measure that input voltage level which results in the appropriate worst-case output voltage level (V_{OH} (MIN) or V_{OL} (MAX)).
(b) Utilize test method 3011 except the output terminal shall be forced to the specified value of V_{OL}.



a. Curve Tracer



b. X-Y Recorder

FIGURE 8.1. TWO TECHNIQUES FOR MEASUREMENT OF IMPEDANCE CURVES

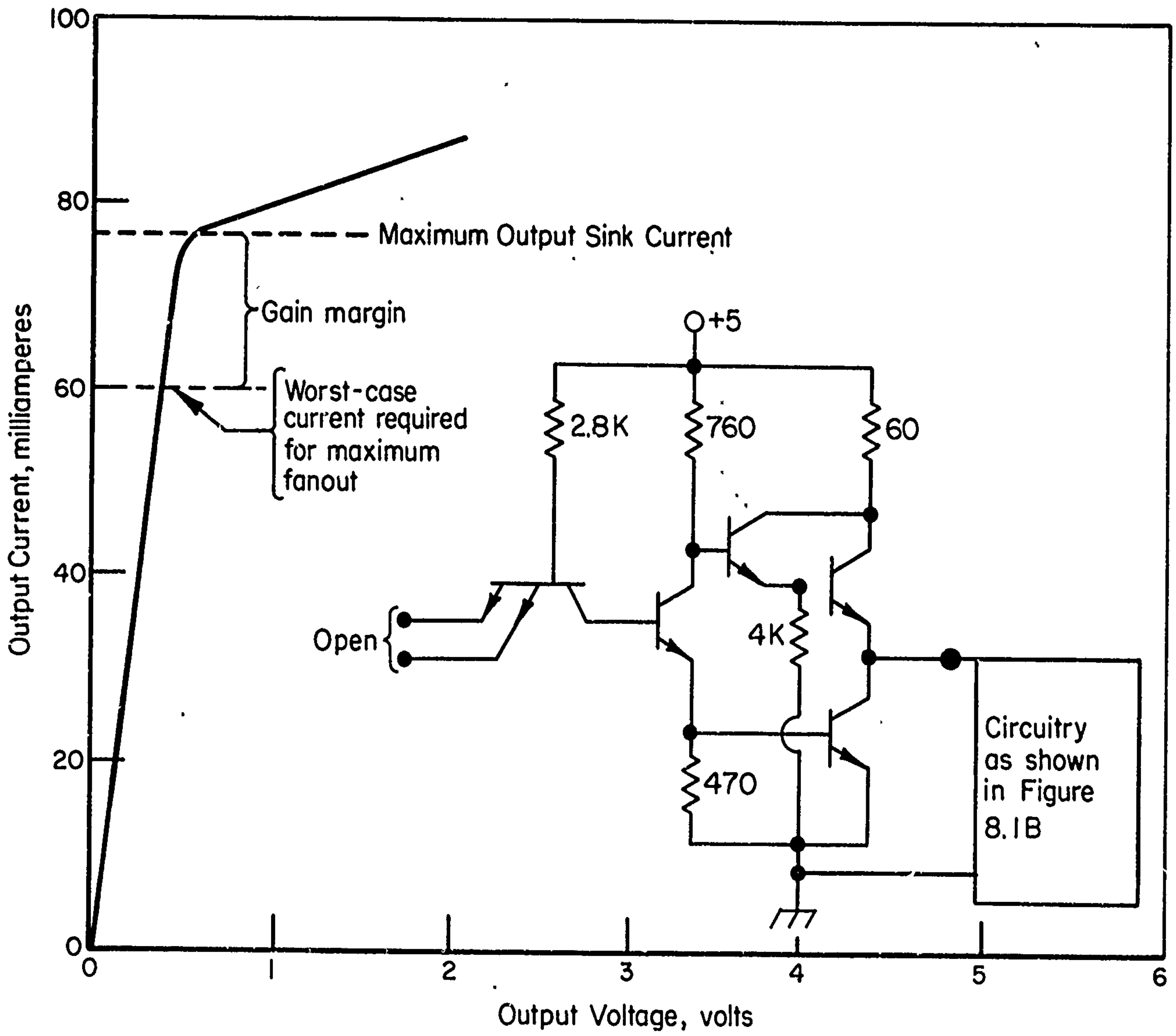


FIGURE 8.2. MAXIMUM OUTPUT SINK CURRENT FOR A TTL GATE

Switching Performance

Accurate switching measurements on modern logic circuits can be difficult to make. It is not uncommon to encounter differences of 20 percent in propagation delay times between results from two different laboratories. This occurs because of a host of experimental difficulties, including the stray capacitance, amplitude and rise time of pulse generators, and the high-frequency characteristics of the test fixture which influence the amount of ringing observed on the signals. These problems are most severe for high-speed circuits and should not be undertaken unless the application is very critical and small changes can affect the operation of the system. If the characterization is to be undertaken, because of the difficulties, it is recommended that changes in switching time with neutron and gamma ray degradation should be reported along with the appropriate impedance measurements for the circuits. The reasons for this are: (1) switching times are sensitive to load capacitance, and often the data can be extended to other capacitive load conditions if the output impedance curve data is available, (2) the accuracy of the impedance curve measurement is usually much better than that of switching measurements, and this enables an assessment of the quality of the data by comparing switching time data with calculations of switching time changes based on the impedance curve data. Appropriate procedures for measuring switching time are described in MIL-STD-883 Methods 3004. Propagation delay measurements are described in MIL-STD-883, Method 3003.

Rapid Annealing Measurement

There are two parameters and two possible bias conditions under which the experimenter might wish to obtain an indication of rapid annealing in a digital circuit. The circuit could be biased or unbiased during irradiation. The effects which result from the two conditions should be different because in one case all internal devices are off and in the other only certain devices are exposed while off. The parameters of primary interest would be propagation delay and/or source (or sink) current. The measurement circuit to be used should be like those previously specified for characterization of these parameters with the addition of a mechanism for removal of power during exposure. When performing these tests the experimenter should understand that the transient annealing measurements are complicated by the photocurrents generated by the gamma radiation accompanying a neutron pulse. For meaningful data analysis the gamma dose rate must be monitored during a rapid annealing experiment. Note that from 1 to 10 percent of the maximum gamma dose rate can persist for milliseconds after the neutron pulse. For this reason, extreme care should be exercised in analyzing rapid annealing data.

Specific Example of a Neutron Irradiation Test of Digital Microcircuit

To characterize the neutron-induced permanent electrical degradation of the microcircuit illustrated in Figure 8.3, electrical parameters were monitored before and after each radiation exposure. The microcircuit was exposed in an unbiased condition which completely eliminated the requirement for on-site test equipment and also presented a worst-case condition for radiation degradation. Characterization then consisted of exposing the device at multiple neutron fluences and evaluating the device electrical parameter degradation as

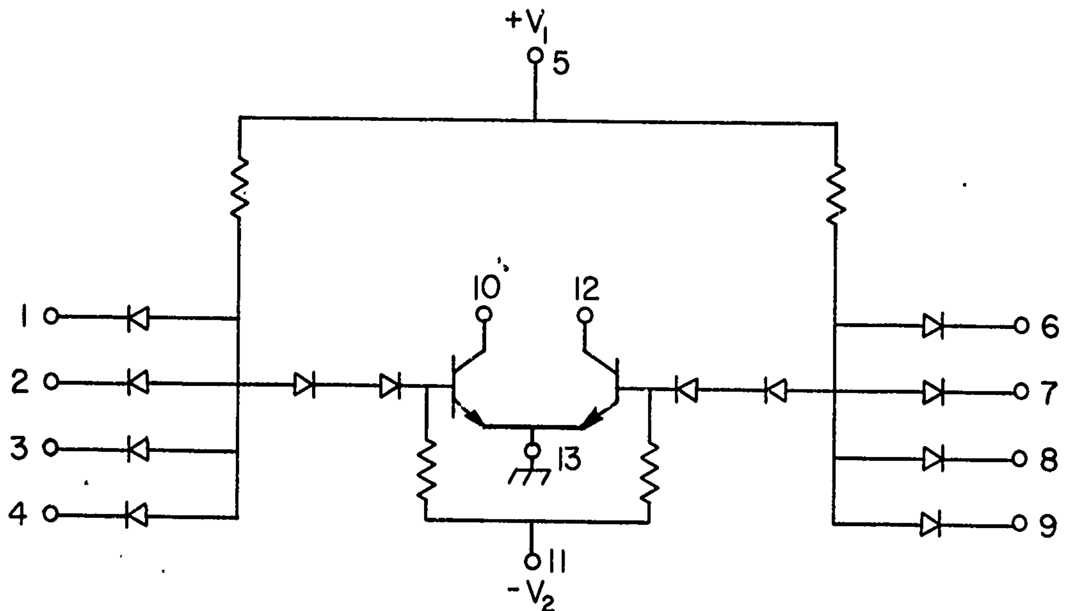


FIGURE 8.3 DUAL NAND GATE

a function neutron fluence. Table 8.3 lists the electrical parameters of this device type, which were specified and measured to demonstrate that the device would meet the system electrical requirements, prior to exposure in a radiation environment. This electrical acceptance test ensured the devices would perform properly in the system by the application of system worst case power supplies voltages (V_1 and V_2) and the worst-case sequencing of power supplies and/or input signals where applicable. For the NAND gate under discussion, sequencing is not critical, but V_1 and V_2 were changed as required to those maximum or minimum values which provide a worst-case reading of the parameter under test. The nominal bias voltages were not used for device electrical tests. These parameters were tested with automated test equipment; thus, the same parameters are also measured automatically after each radiation exposure. The radiation characterization permits the design engineer to establish quickly those electrical parameters that are most sensitive to this environment, determine design safety margins, and define appropriate postradiation values for future part hardness monitoring. For the NAND gate in the example, the saturation voltage of the output transistors has proven to be the electrical parameter that has the greatest system impact after neutron irradiation.

TABLE 8.3 DUAL NAND GATE ELECTRICAL PARAMETERS

Power Supply Currents
Low Level Input Current
High Level Input Current
Low Level Output Voltage
Low Level Output Current
Propagation Delay Times

Specific Linear Circuit Test Procedures

General Measurements

The problems involved with measuring linear circuits pre and post-irradiation are not much different than if they were to be characterized for normal useage. For in situ measurements, the primary precaution should be to insure that the devices will not oscillate when they are operated at the end of long cables. It may be necessary to utilize a cathode follower line driver to avoid excessive loading of the device outputs (see discussion in Section 2.5). Therefore, the test methods outlined in MIL-STD-883 with the necessary modifications are recommended as the preferred measurement circuits. The parameter and appropriate test methods are in Table 8.4.

TABLE 8.4 PREFERRED MEASUREMENT CIRCUITS FOR LINEAR CIRCUITS

Parameter	Method From MIL-STD-883
Circuit Gain	4004
Input Bias Current	4001
Input Offset Current	4001
Input Offset Voltage	4001
Frequency Response	4004
Slew Rate	4002
Output Dynamic Range	4004
Noise Figure	4006

The listing of these measurements does not imply that these measurements all should be made. Measure only those which suit the purpose of your experiment.

Rapid Annealing Measurements

When performing rapid annealing experiments, two considerations are necessary. The first consideration is to determine whether the circuit is to be biased or unbiased during exposure. If the circuit is to be continuously biased during irradiation then the appropriate circuit as described above will be sufficient. If, on the other hand, the circuit is to be unbiased during exposure, the circuits described above will have to be modified so that the circuit under test can be turned on quickly. In addition, the experimenter will be required to characterize the circuit's response to turn-on both before irradiation and immediately after the rapid anneal. A cathode follower line driver may be needed to avoid excessive loading of the device outputs. Finally, the experimenter should be aware that transient annealing measurements are complicated by the photocurrents generated by the gamma radiation accompanying the neutron pulse.

Figure 8.4 shows an example of annealing data for a simple linear amplifier. The circuit was biased during irradiation, the voltage gain was measured with a fixed input level, and an active line driver was used to avoid loading the amplifier with the cable termination. The gamma radiation present in the reactor caused a transient response which complicates the interpretation of the data at short times after the pulse.

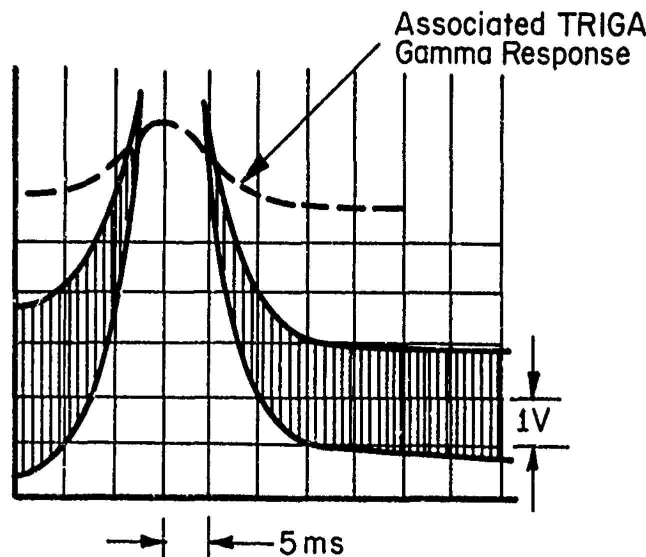


FIGURE 8.4 μA741 OPERATIONAL AMPLIFIER
TRIGA Pulsed Neutron Response.

Specific Example of a Neutron Irradiation Test of a Linear Microcircuit

As in the NAND Gate Example, the differential amplifier illustrated in Figure 8.5 was tested electrically on automated test equipment with the application of system worst-case values for V_1 and V_2. These devices were also exposed at several different neutron fluence levels and the complete electrical tests performed before irradiation and after each radiation exposure. These data were also used in the same manner as the data on the NAND Gate; electrical parameter degradation was evaluated as a function of fluence from which system safety margins and critical parameters were determined.

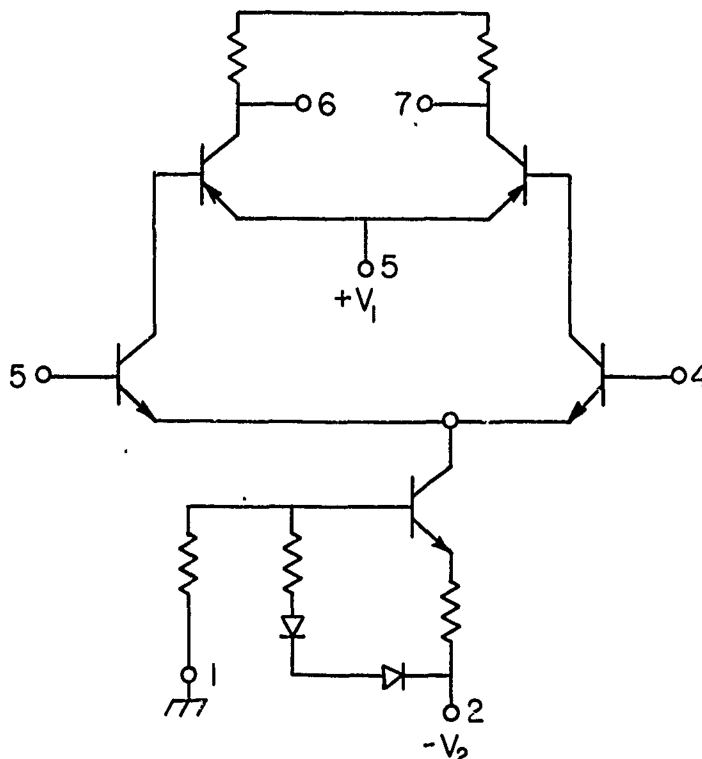


FIGURE 8.5 DIFFERENTIAL AMPLIFIER

Table 8.5 lists the electrical parameters of this device type which were specified and measured before irradiation and which were monitored after each radiation exposure. The ac voltage gain, input impedance, and common mode output voltage offset had the greatest system impact under neutron irradiation for the differential amplifier in this particular example.

TABLE 8.5 DIFFERENTIAL AMPLIFIER ELECTRICAL PARAMETERS

Power Supply Currents	Upper Cutoff Frequency
Differential Input Voltage Offset	Differential Input Current Offset
Common Mode Output Voltage Offset	Input Impedance
Low Frequency Voltage Gain	Common Mode Rejection Ratio
Output Signal Swing	

8.3 TRANSIENT-RESPONSE MEASUREMENTS

Transient Ionization Effects

The transient effects observed in integrated circuits are due to the generation of excess charge carriers that cause circuit currents and voltages to change. The result of these changes can be temporary (transient) or permanent (catastrophic). For digital circuits, the transient changes manifest themselves as apparent changes in output voltage states and as power supply current surges. Transient response in linear circuits also appears primarily as an output voltage pulse or power supply current surge. The magnitude and duration of these effects depends on the type of component isolation within the circuit, the type of component within the circuit, the circuit configuration and the loading configuration of the circuit. Relative magnitudes of device response for use as testing guidelines can be obtained from Section G of the TREE Handbook, Volume I.

Catastrophic Failure

Metallization and Junction Burnout in Microcircuits

High current surges which are induced in a microcircuit by transient radiation may cause junction burnout or metallization failure because of power dissipation in the device. Metalization burnout usually occurs at locations where thinning of the metallization occurs, such as sharp bends or when the metallization crosses over a step in the surface oxide.

Circuits that have diffused resistors are more susceptible to metallization failure and junction burnout because the resistor value drops significantly during a high-intensity transient pulse. Circuits that are junction-isolated are also more prone to burnout problems because the substrate photocurrent is very large, and there will be large transient currents flowing at high radiation levels.

Microcircuit Latchup

Microcircuit latchup has been observed for a few of the many circuit types tested in a transient environment. Latchup is defined as a permanent (dc) or long-term ($\geq$100 μs) transient response which is not simply caused by transistor storage time or risetime, and affects the operation of the device. The latchup is usually dc, and normal circuit operation can be restored if the device has not burned out by temporarily interrupting circuit power.

Three latchup mechanisms have been considered in junction-isolated integrated circuits. They are PNPN action, second breakdown, and voltage breakdown of the transistor. Although all three mechanisms have been observed in structures within an integrated circuit, only PNPN action and second breakdown have caused circuit latchup. The mechanisms of integrated circuit latchup are discussed in the TREE Handbook, Volume I, Section G.

Both junction-isolated and dielectrically isolated integrated circuits can be designed to be latchup-free. However, circuits that have not had the considerations of radiation-induced latchup factored into their design must be analyzed and/or tested to determine their susceptibility to latchup.

Parameters Discussed

It is generally agreed that the most valuable ionization-effects data for the system designer are specifications of transient output response as a function of dose rate for fixed bias conditions and known ionizing-radiation dose-rate profiles. In addition, the power supply transient (due to excessive current drain) is a parameter of interest to the designer. If there are significant power-supply transients occurring in a system, they can cause changes in circuit bias conditions which could lead to latchup or an unexpected system response.

The output and supply current transient responses can be characterized by either a voltage or a current measurement method. In addition, a method for measuring possible latchup response is indicated.

Test Considerations

The reader is referred to Section 2.5 for a general discussion of test considerations. Some additional test considerations that relate specifically to microcircuits are outlined below as an aid to experimental design.

At least a minimal pretest check is always necessary to verify that the intended sample is electrically and mechanically satisfactory. For samples used to generate basic design data for a system, it should be established that all samples meet the purchase or application specifications for that part number prior to testing. Device permanent damage can occur due to electrical or radiation accidents or photocurrent stresses. The risk is greater in tests at high dose rates [greater than 10^9 rads (Si)/s]. It is recommended that tests be made before and after irradiation to verify satisfactory electrical response.

The response of microcircuits depends upon the radiation pulse width. When measuring responses to a pulse of ionizing radiation, it is helpful to know the time required to establish photocurrent equilibrium in the circuit during irradiation. Figure 8.6 illustrates the dependence of the circuit radiation response on the pulse width for a typical circuit. If the radiation pulse width is less than the equilibrium time, the response is dose dependent. If the radiation pulse width is longer than the equilibrium time, the response is usually dose-rate dependent. The circuit equilibrium time can be determined from a set of data such as that shown in Figure 8.6 or from a measurement of the unsaturated response to a square pulse of uniform intensity whose pulse width is greater than the equilibrium time. Such a response will look similar to the plot in Figure 8.6 where the abscissa is time instead of pulse width.

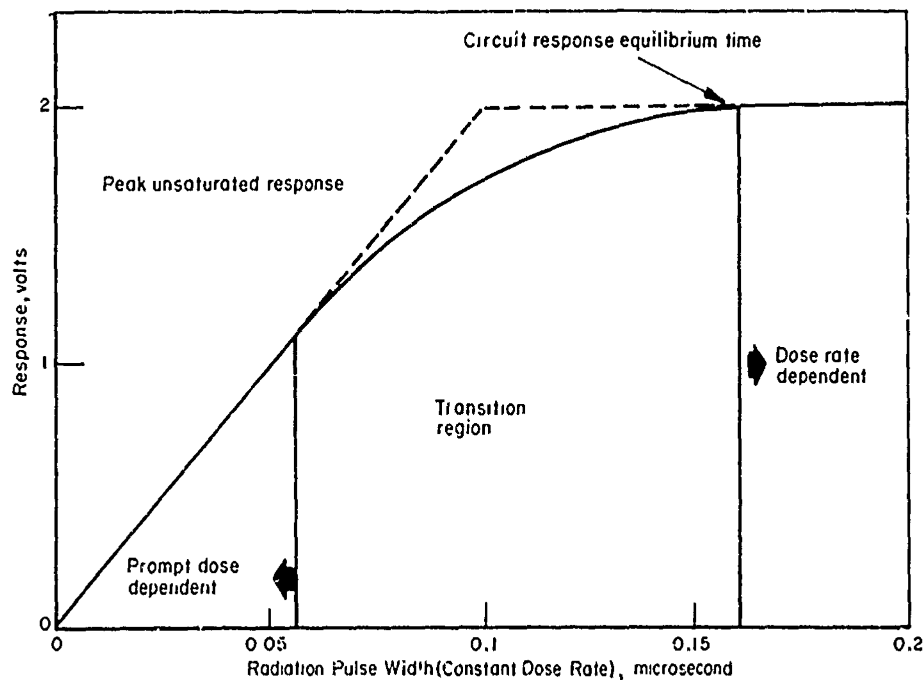


FIGURE 8.6 RADIATION PULSE DTH DEPENDENCE OF THE CIRCUIT RESPONSE SHOWING THE DOSE AND DOSE-RATE DEPENDENCE REGION

It is important to emphasize that the circuit's transient responses to radiation can be sensitive to electrical loading of both the input and output. Therefore, the electrical load on a circuit should always be reported. As an example, many digital circuits are sensitive to excessive capacitive loading. This of course is a greater problem for those circuits with high output resistance. For this reason, many digital circuits are more sensitive to ionizing radiation at low fanout; hence, they should be tested in this condition for their "worst-case" results. The transient radiation failure threshold can increase by a factor of two to three for higher fanout conditions. Linear circuits also are influenced by electrical loading. Generally, one of the most sensitive portions of these microcircuits is their response to the input transistor primary photocurrent, which, if forced to be dropped across a high impedance

(either resistive or inductive), will produce a much larger disturbance and hence a lower ionization threshold. For differential amplifiers, the mismatch in the source impedances at the inputs can greatly affect the transient response. Highly unbalanced source resistances make the circuit more sensitive to radiation. Circuits that typically have widely differing source impedances (such as operational amplifiers) should be tested using the highest input impedance condition. The response of other components in the circuit application sometimes can cause problems. In one application, a tantalum capacitor was placed at the input of an op-amp so that it was only loaded with a high dc resistance. Long-term voltage buildup in the capacitor (this occurred for several minutes after the radiation pulse) caused the amplifier output to be affected. This problem was caused by radiation effects on the capacitor which were overlooked in the initial experimental design. Whatever the cause, a measurement of the circuit impedance will help to determine if the circuit response is sensitive to loading variations. When the response is sensitive to loading, at least two values of load impedance should be used to determine the output impedance during irradiation.

Table 8.6 summarizes general loading and operating configurations that could be used for determining device response.

TABLE 8.6 LOADING AND OPERATING CONFIGURATIONS FOR CIRCUIT RESPONSE TESTING IN PULSED IONIZING ENVIRONMENTS

Circuit Type	Response Measured at	Loading	Operating Configuration
Digital	Output(s)	Fanout 1	1 State (Output) 0 State
	Power Supply(ies)	--	--
	Input(s)	Low Impedance High Impedance	0 State (Output) 1 State
	Access Nodes	High Impedance	1 State (Output) 0 State (Output)
Linear	Output(s)	Low Impedance High Impedance Low Impedance High Impedance	Open Loop[a] Open Loop[a] Closed Loop Closed Loop
	Power Supply(ies)	--	--
	Input(s)	Low Impedance High Impedance	-- --
	Dual Inputs	Worst-Case Mismatch	--
	Access Nodes	High Impedance	--

(a) This may not always be possible.

When repetitive pulsing is employed or when high dose rates and/or long pulse widths are used, it is easy to build up large doses in the sample. A dose of about 10^4 rads(Si) is the threshold beyond which some devices may incur significant permanent damage. When this threshold is exceeded, the sample dose should be reported, and a clear identification made of the data that were obtained above the threshold. Justification should be given for using such data.

When testing only to determine threshold values, it is suggested that a few samples be checked to determine the relative location of the threshold. The remaining samples can then be tested over a more limited dose or dose rate range to establish their specific threshold values.

An additional experimental problem is introduced if the operation of the circuit under test has to be synchronized with the radiation pulse. Often the experimenter cannot pulse the radiation source remotely to coordinate the desired radiation with circuit operation. Often, however, the facilities provide an equipment trigger signal. The difficulty is in trying to use it as a synchronizing signal. There is an inherent variation (jitter time) in the delay between the actual trigger signal received by the test equipment and the radiation pulse. To determine whether the jitter time for a particular experiment will be acceptable consult both the Simulation Facilities Handbook DASA-2432 and the facility operator.

Adequate documentation of the methods and results of transient-effects experiments cannot be overly stressed. The following data should be recorded for each radiation burst.

- Identification of all test equipment including accuracy and scale factors
- Exact experimental configuration including shielding and grounding schemes
- Type of ionizing radiation
- Energy spectrum of the incident radiation
- Radiation-pulse shape
- Radiation-pulse width
- Dose rate in the sample material
- Accumulated dose in the sample material
- Sample identification
- Voltage bias on the sample
- Sample orientation
- Case connection

- Ambient temperature
- Pictorial representation of device response.

Specific Test Procedures for Both Digital and Linear Circuits

The voltage and current measurement techniques discussed below are basically the same as those described in Subsection 6.2. It is suggested that the reader review that subsection prior to reading the following material. Note that very often more than one measurement is made at a time in testing microcircuits. For example, the experimenter might observe the output voltage, an input voltage, and a power supply current all at the same time.

Finally the reader should remember that the material presented here outlines basic principles and problems with which the experimenter should be familiar. It will be up to the experimenter to correctly adapt the appropriate material to his unique experimental problem.

Voltage Measurements of Device Photoresponse

Voltage measurements are usually required when testing the output response of microcircuits in a pulsed ionizing radiation environment.

A block diagram of a typical circuit for voltage measurement during ionization testing is shown in Figure 8.7. Although this figure illustrates a digital circuit under test, the measurement circuit is easily adaptable to linear circuits. A linear circuit test configuration is shown in Figure 8.8. The cable between the experiment and the line driver should be kept short to minimize capacitive loading and replacement currents. The power supply capacitor C must be large enough to supply the transient current and remain a stiff voltage source during the radiation transient. The time constant R_2C must be large compared to the period of the noise signal induced in the long cable. A convenient method of checking this is to drive the circuit input using a pulser. Shielding of cables and active instrumentation might be necessary if the beam area is large. If a digital circuit is to be checked at both output levels, then some convenient arrangement such as a relay or solid-state switch should be incorporated in the measurement circuitry to change the input bias level.

Active line drivers are frequently employed in these measurements as illustrated in Figure 8.6. However, they must be carefully designed and generally require severe tradeoffs among linearity, input impedance, signal swing capability, and capacitive loading. These problems are discussed in Section 2.5. Often the problem is to reduce the signal to a value that can be handled by the secondary equipment. In this case, attenuators are needed. Attenuators are also discussed in Section 2.5.

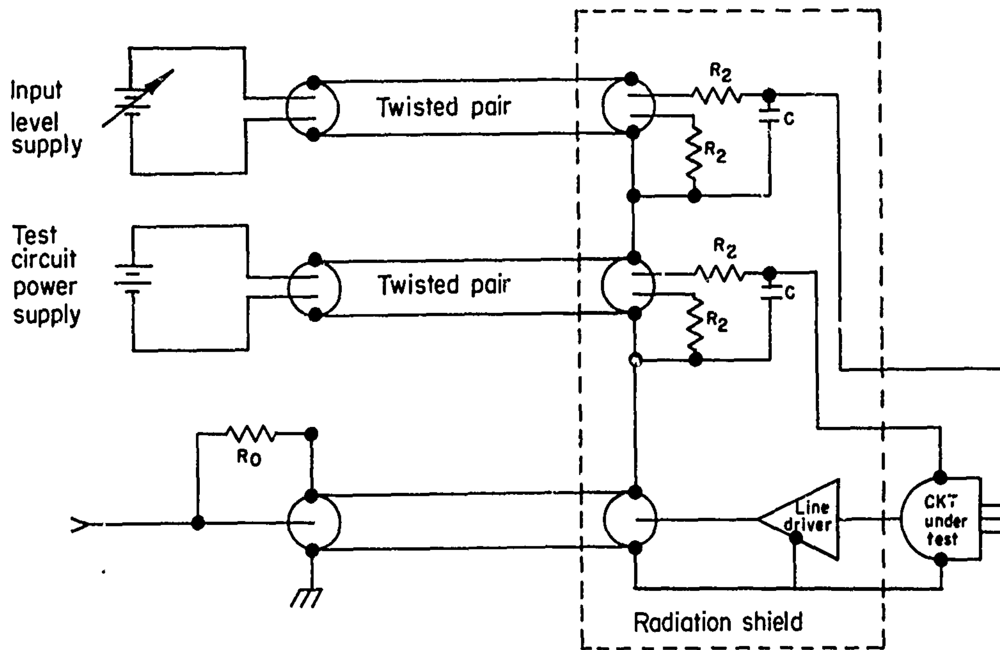


FIGURE 8.7. TYPICAL TEST CONFIGURATION FOR TRANSIENT IONIZATION TESTING (LOGIC CIRCUITS)

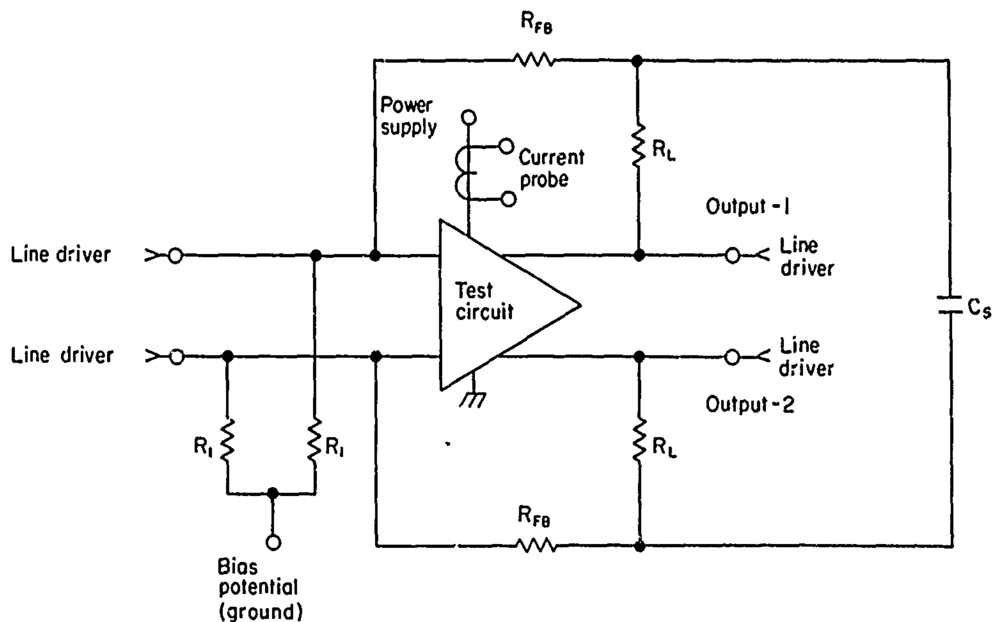


FIGURE 8.8. TYPICAL TEST CONFIGURATION SHOWING MONITOR POINTS FOR A DIFFERENTIAL AMPLIFIER IN A DC STABILIZED OPEN-LOOP CONFIGURATION

While differential measurements can be used in radiation testing, their application to narrow, fast-rise-time radiation testing is not straightforward. Before differential measurements are made, cable lengths must be matched within a few inches, and a suitable oscilloscope must be selected. Commonly available dual-trace plug-ins do not have adequate common mode rejection in their "add algebraic" mode for pulses with fast rise times. Special plug-ins (such as the Tektronix 1A5) are specifically designed for differential applications. Once the necessary electrical criteria are satisfied, the user must worry about replacement currents. Unfortunately, replacement currents vary with the physical location of cables and the voltage applied to the center conductor. The spurious voltage due to a replacement current also depends upon the source impedance of the device during the radiation pulse. These factors make it difficult to estimate the degree of cancellation of spurious signals for differential measurements in radiation testing. For most microcircuit characterizations the differential technique is rarely used because of its problems. If, however, differential techniques are to be employed, careful attention should be given to the problems mentioned above.

Current Measurements of Device Photoresponse

During exposure to ionizing radiation, the system power supply voltage may slump due to an excessive transient current drain. Thus it may be important to characterize the power supply current of the microcircuit under test. The power supply current measurement is particularly important for junction isolated microcircuits.

Preferred test circuits are given here for the measurement of device current photoresponses. The two basic techniques illustrated here – the resistor-sampling method and the current-probe method – are discussed in Section 6.2.

The current-probe technique is used when minimum deviation of the operating point is required. Although this method of measuring current is less sensitive (1 mV/mA) than the resistor sampling technique it is capable of measuring larger currents. The upper limit of the measurement can be made dependent only upon the saturation limit of the current probe. The low-frequency cutoff of such probes may make them inadequate for wide pulse widths. The insertion impedance of the probe should be considered. It can happen that the L (di/dt) voltage drop is sufficient to cause the output to change states. The probe should always be positioned between the bypass capacitor and the circuit under test (see Figure 8.9).

The circuit configuration for one-lead measurement is shown in Figure 8.9. The circuit components are defined as follows:

- V - A voltage source set to the required bias
- R_0 - The cable characteristic resistance

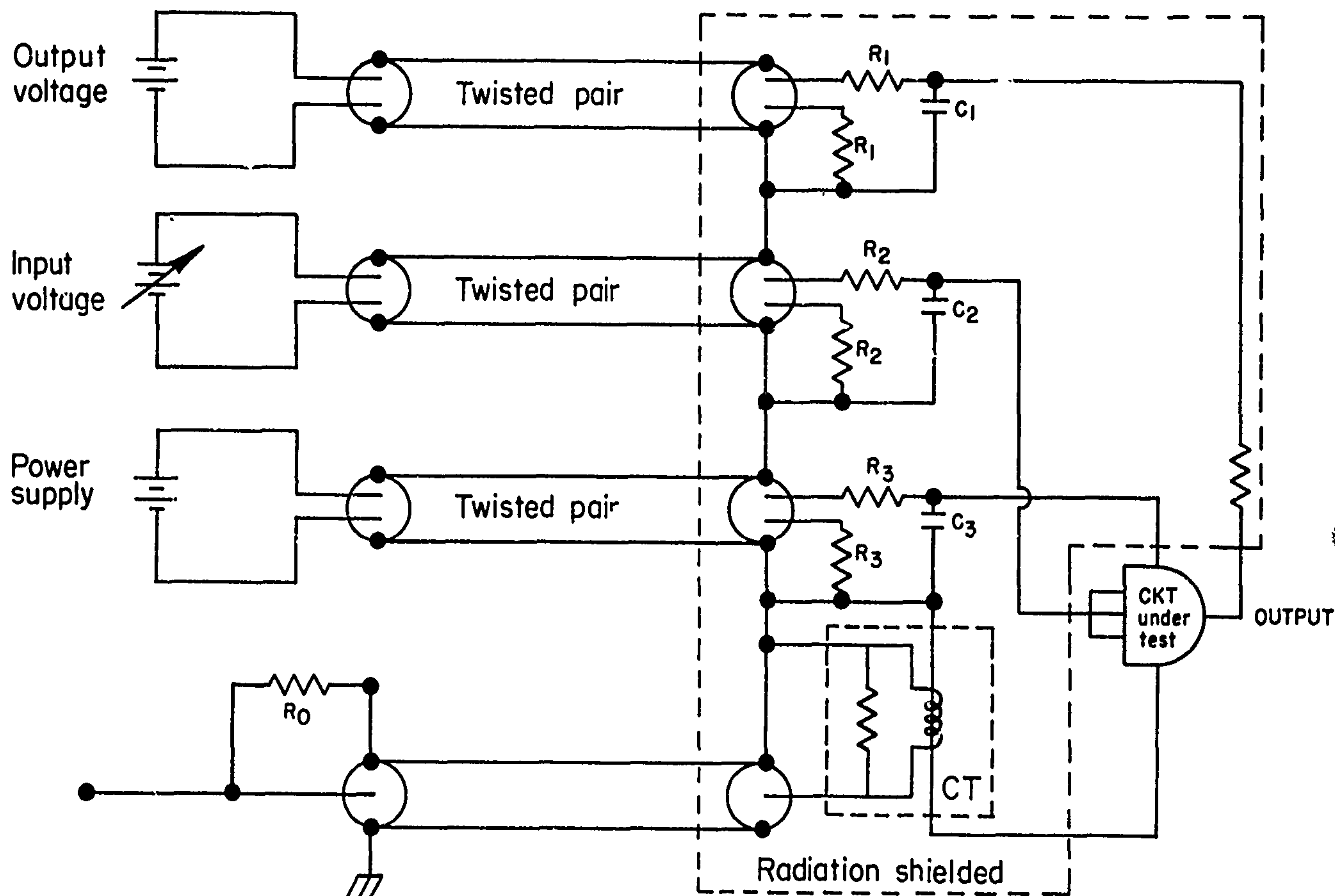


FIGURE 8.9. ONE-LEAD, CURRENT-PROBE MEASUREMENT

See Figure 8.8 for illustration of adaptation of this test circuit configuration to a linear circuit.

- $R_{1,2,3}$ - Selected to give high frequency isolation and yet small enough to permit proper dc current in the device
- $C_{1,2,3}$ - An effective bias-supply bypass (the time constant RC should be large compared to the period of the noise signal induced in the long cables)
- CT - A current probe with suitable response characteristics
- I_{pp} - is photographed on a suitable oscilloscope.

Latchup Test

As there is no simple test procedure for latchup, the procedure to be used depends upon the results of an analysis of each microcircuit type. When microcircuits are tested for latchup in a pulsed ionizing radiation, it is very important to be able to save those devices that have shown latchup so that they can be examined to determine the cause of latchup. Therefore, it is important that the power to the microcircuit under test be removed shortly after the irradiation pulse (50-100 μs). The test circuitry should allow for observation of both the output signal and the power supply current. The necessary voltage and current measurement techniques have been discussed. The circuit operating parameters during test (terminating impedances, applied voltages) must be determined by the analysis; they may not be identical to those used in the actual system application. This difference occurs because the circuit irradiation tests are normally performed with fixed terminating impedances and fixed applied voltages, while in the system application – where the whole system is irradiated – terminating impedances and applied voltages may be varying during the circuit irradiation. Therefore, the test configuration of the circuit should be designed to maximize the chance of observing either a latchup or a change of circuit performance. A change in circuit-performance characteristics indicates a change of circuit device parameters that may then be related to a possibility of a latchup. The important point here is that a test in which a circuit with either the maximum or the minimum terminating impedances and voltages that are used in the system application may not catch all the devices that will exhibit latchup when the total system is irradiated.

Specific Examples of Ionizing Radiation Tests

Frequently semiconductor microcircuits are used in computers or other electronic subsystems that have a logic-change inhibit or circumvention capability that preserves the existing logic states at the initiation of an ionizing radiation pulse. The circumvention signal is initiated by a radiation detector circuit, the heart of which is an ionizing radiation sensitive semiconductor. The radiation sensitivity (threshold) of the circumvention circuit is normally set very low relative to that of the associated microcircuits in order to prevent logic errors occuring from a change in a microcircuit logic

state at a lower radiation dose rate than the detector threshold. Individual microcircuits are characterized under ionizing radiation by determining the level of their transient outputs as a function of ionizing radiation dose rate; thus, providing the circuit designer with knowledge of the system safety margin for each microcircuit type. If circumvention is not used in the system, the preceding characterization provides the design engineer with knowledge of the radiation level at which his system will begin to experience radiation-induced logic errors. Depending upon the function of a particular electronic subsystem, one or more logic errors may only degrade the system performance rather than produce catastrophic system failure.

Another concern of the design engineer is the possibility of catastrophic microcircuit failure caused by a high-intensity prompt ionizing radiation pulse producing burnouts. Thus, the designer should have his microcircuits characterized under high intensity prompt ionizing radiation, or qualified at a level sufficiently above his criteria that he has high confidence in microcircuit survivability at the criteria level.

Digital Microcircuit Example. Figure 8.10 is a schematic of a 4-channel dielectrically isolated integrated circuit switch that has been characterized for both low-level and high-level ionizing radiation. Figure 8.11 shows the switch as a black box and indicates the biases and associated circuitry used in performing low-level ionizing radiation characterization of this part. Each part to be characterized in ionizing radiation, first receives an automated electrical verification test using worst-case biases, to demonstrate that the part is suitable for system usage prior to irradiation. Because of the similarity of the four channels in this switch, only the outputs at pins 6 and 11 are monitored, as transistors Q_1 and Q_4 do not have any internal current limiting resistors, i.e., R_3 and R_4. The switch, S_1, in Figure 8.11 is opened before and after irradiation, demonstrating the integrity of the test setup and test device by causing transistors Q_1 and Q_4 to saturate which causes the output voltage at pins 6 and 11 to be approximately +5 volts. During irradiation, S_1 is closed, which turns off transistors Q_1 and Q_4, the voltage at pins 6 and 11 is a steady-state value of approximately -3 VDC. Since the transistors of the given switch only operate in two logic states, true and false, and since ionizing radiation tends to drive transistors into the true state, the characterization is performed with both transistors in the false state. In addition, since transistors act as current generators under ionizing radiation and the device threshold is defined as an increase in output voltage of 1.2 V, the device is tested under minimum fanout conditions, representing worst-case system requirements.

During low-level ionizing radiation characterization (threshold), a LINAC operating in the electron beam mode provides the radiation environment as a rectangular pulse. The radiation intensity is monitored by recording the output of a precalibrated back-biased diode which has a radiation response that is linear with dose-rate for the dose rates normally encountered in this test. The threshold characterization is performed by monitoring

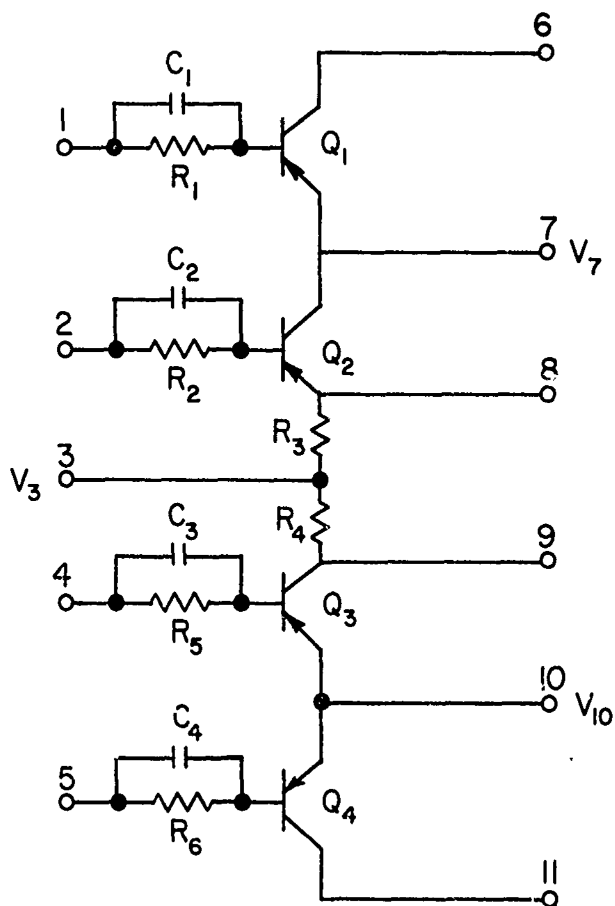


FIGURE 8.10. FOUR CHANNEL DIIC SWITCH

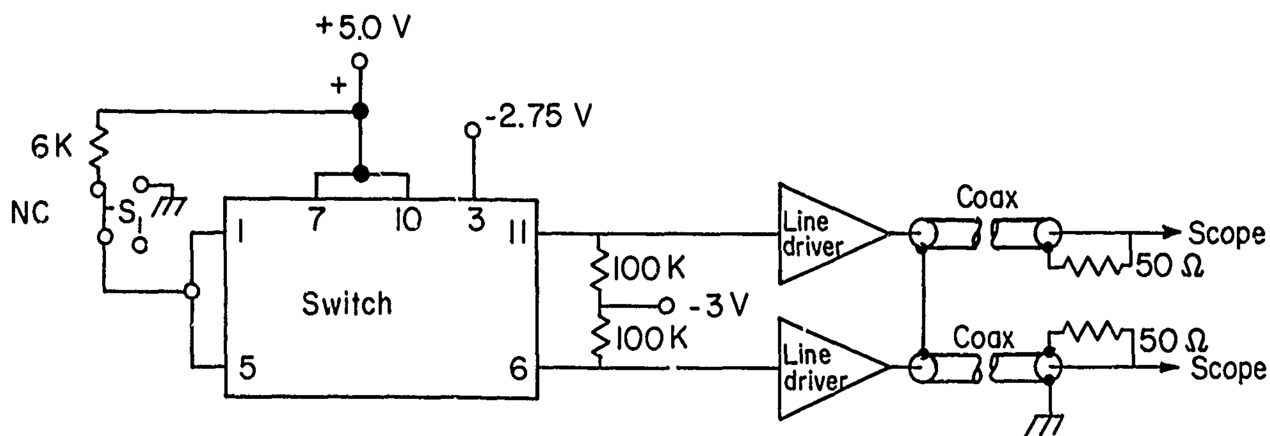


FIGURE 8.11. LOW-LEVEL IONIZING RADIATION TEST SETUP FOR SWITCH IN FIGURE 8.10

the change in voltage at pins 6 and 11 as a function of radiation dose rate. Output voltage change is then plotted as a function of dose rate, and the threshold is obtained by determining that dose rate at which the output voltage has changed by 1.2 volts.

Characterization of this part under high-intensity ionizing radiation also consists of a preirradiation automated electrical test to demonstrate the part is good and is concluded with an identical postirradiation electrical test to demonstrate that the part has sustained no permanent damage or degradation. During the radiation characterization, the switch is powered and loaded as shown in Figure 8.12.

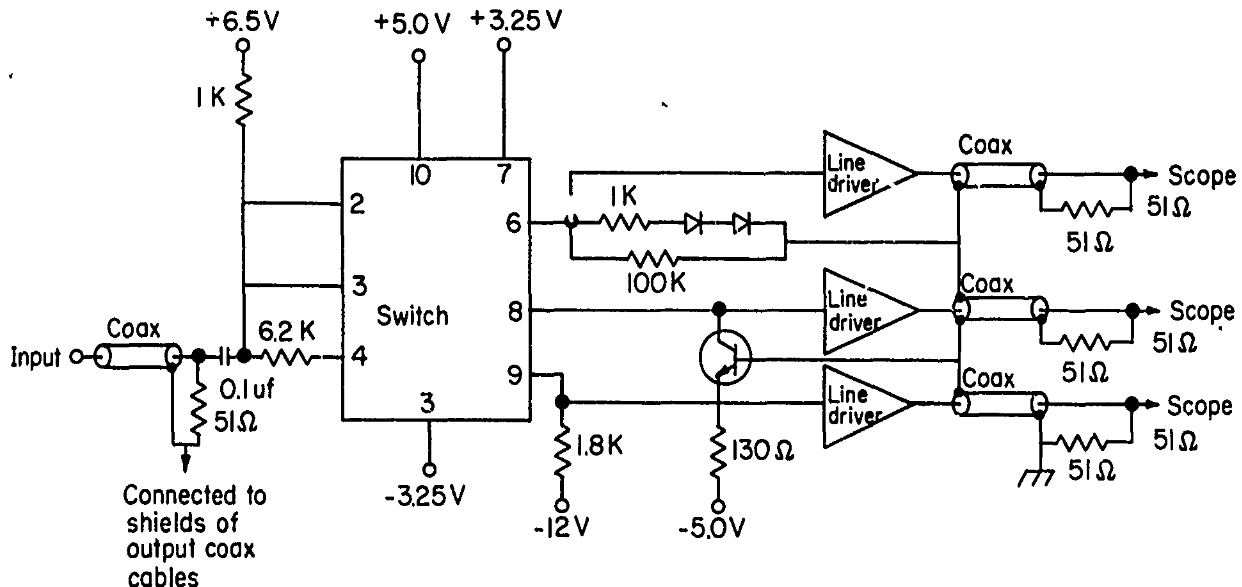
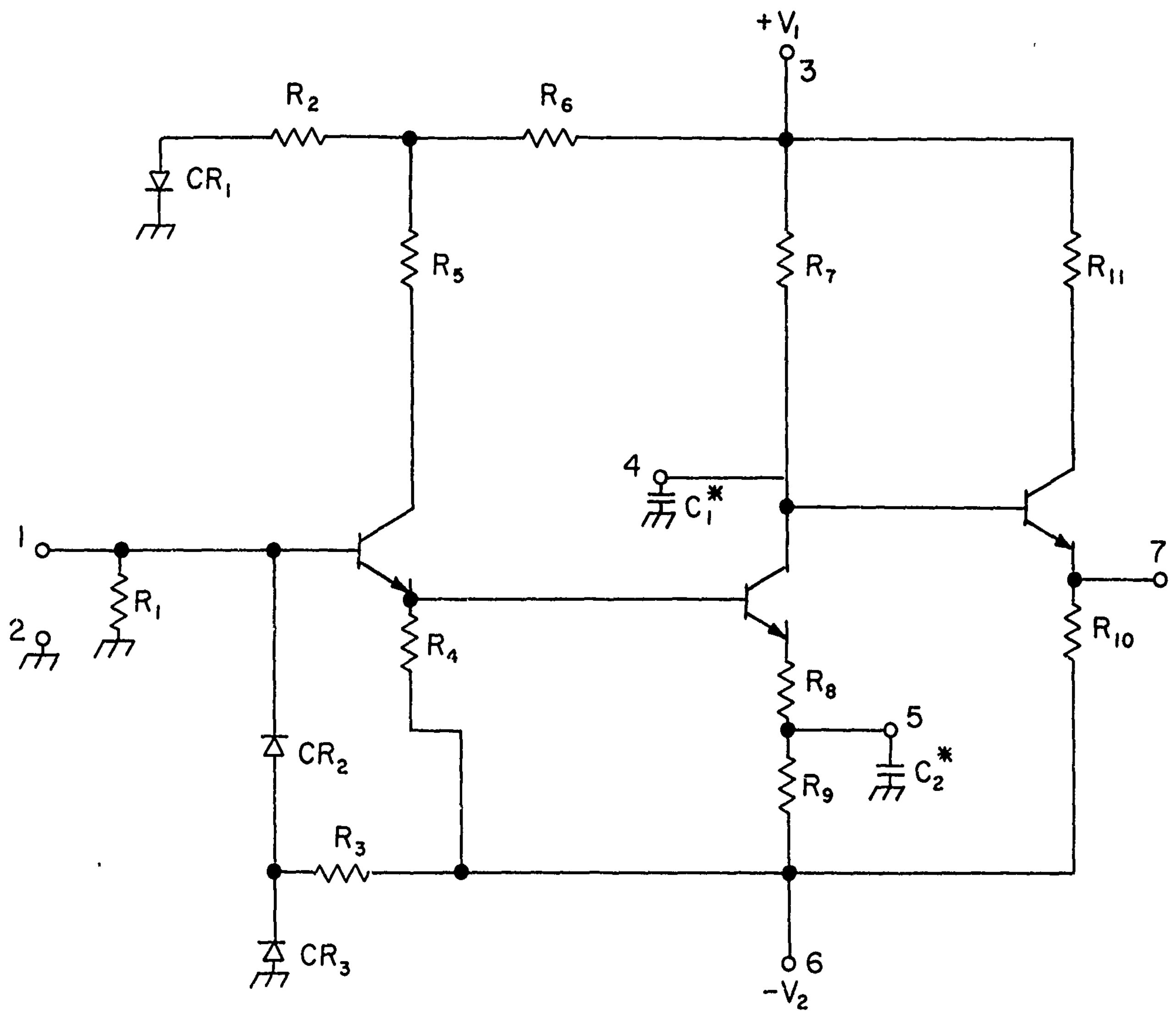


FIGURE 8.12 HIGH-LEVEL IONIZING RADIATION TEST SETUP FOR SWITCH IN FIGURE 8.10

An electrical input pulse is transmitted to the switch just prior to and just after a radiation exposure to demonstrate that catastrophic failure has not occurred. As indicated in Figure 8.12, three of the switch outputs are loaded with typical worst-case system loads to verify the hardness of the part in all circuit applications.

Radiation characterization is performed by exposing the device to successively larger radiation pulses from a flash X-ray machine operating in the electron beam mode, and monitoring the output transients, recovery times, and radiation doses on each test part. The recovery time is monitored to demonstrate that the device has not latched up or been forced into second breakdown. With small signal dielectrically isolated microcircuits such as these, neither failure mode has been observed. As stated above, the postradiation electrical test has verified that photocurrent surges have not burned out any metallization stripes in this device type.



* C_1 and C_2 are discrete capacitors and are not irradiated during characterization.

FIGURE 8.13. TYPICAL LINEAR AMPLIFIER THAT HAS BEEN CHARACTERIZED UNDER IONIZING RADIATION

Linear Microcircuit Example. The high-intensity ionizing radiation characterization philosophy given above for digital microcircuits also applies to linear microcircuits; a linear microcircuit must not fail catastrophically nor may its radiation-induced transient output have a recovery time in excess of that required for system operation.

A typical dielectrically isolated linear amplifier is shown schematically in Figure 8.13. This linear amplifier was characterized under low-level and high-level ionizing radiation in the same manner as the switch described above. The same radiation facilities were used including the same sequence of automated electrical tests, on-site electrical pulse tests, and radiation exposures.

Figure 8.14 represents the amplifier as a black box and shows the biases and associated test circuitry used in performing low level ionizing radiation characterization.

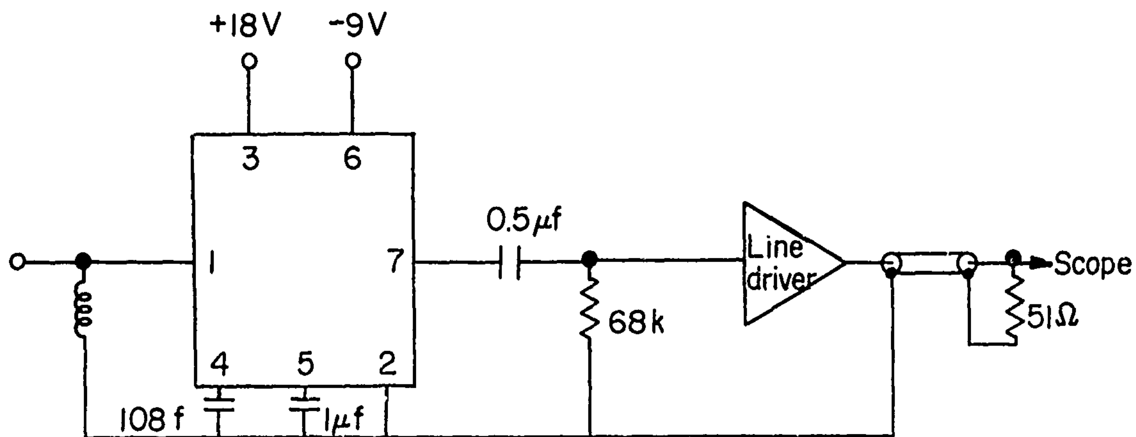


FIGURE 8.14 TEST SETUP FOR LINEAR AMPLIFIER LOW-LEVEL IONIZING RADIATION CHARACTERIZATION

As for the digital switch, the amplitude of the amplifier output voltage pulse is measured as a function of dose rate. That dose rate which causes a shift in output voltage of 0.5 volts is defined as the linear amplifier threshold.

Figure 8.15 shows the test setup for characterizing the linear amplifier to high-level ionizing radiation.

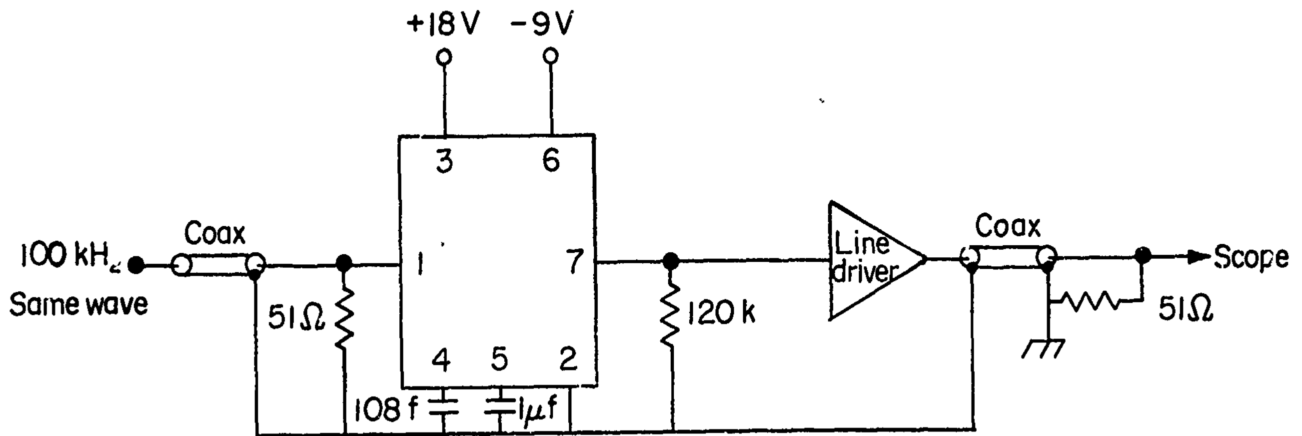


FIGURE 8.15 TEST SETUP FOR LINEAR AMPLIFIER HIGH-LEVEL IONIZING RADIATION CHARACTERIZATION

The only difference between high-level ionizing radiation characterization of the switch and the linear amplifier is that a continuous 100 kHz sine wave is applied to the input of the amplifier which demonstrates that the part is good before irradiation, that catastrophic failure has not occurred because of radiation, and that the ac gain of the amplifier has recovered to within specification limits within the allowed recovery time, i.e., the part has not experienced catastrophic failure or significant electrical degradation caused by exposure to this environment.

8.4 DATA REPORTING

General

The general information required in most reports of TREE tests are given in Section 3.0, "Documentation Requirements". Information requirements covered in that section include reporting of the experimental procedure, a description of the facilities used, the documentation of the dosimetry, and a complete description of the samples irradiated. Included here are specific data requirements for tests involving microcircuits and standardized formats for reporting the data. Table 8.7 shows a typical data format that can be used to present the general information for each irradiation test.

In addition to the irradiation procedure, basic types of samples should be described. A good technique to employ is to provide a separate data sheet that presents the manufacturer, type or specification number, lot

TABLE 8.7 GENERAL INFORMATION

Device Type(s): ______________________________

Facility: ______________________ Date of Test: __________

Dosimetry Method(s): ______________________________

Irradiation Temperature: ______________________________

Experimental Configuration: ______________________________

Electrical Condition During Irradiation: ______________________

(Specify device bias condition and the circuit diagram, including all test equipment and grounding scheme used during in situ measurement.)

Additional Comments:

number, origin (factory, distributor, etc.), and method of selection and validation for the various device types. If useful electrical and structural information (such as power rating and junction areas) is available, it should be reported to facilitate data comparisons and to increase the general utility of the data. A typical parts tabulation sheet is illustrated in Table 8.8.

A statement should be given as to the constancy of any control samples used. The estimated uncertainty in all important results should be quoted. In specifying errors, the value of one standard deviation is the quantity preferred, although other methods may be used if they are more suitable and are unambiguous. When statistical characterizations are given, the techniques involved in their calculation should be explained - at least by a reference.

Due to the large variety of microcircuits and the number of tests that can be performed on them, specific tests conditions cannot be defined on the data sheet itself. Therefore, a separate record is recommended for documenting the measurement conditions by device pin number for each microcircuit test. Table 8.9 is a suggested format for recording measurement conditions. The test designation is necessary to identify each individual test on the data sheets. Either a standard test designation or a number may be used.

In addition to recording the test conditions, the tester is urged to include a test diagram with bias conditions specified.

Permanent-Damage Data

It is recommended that device parameter data be tabulated for each set of measurements giving the parameter(s) measured, the irradiation level at which the measurement(s) was made, the operating condition of the device during measurement, and any additional test conditions. Note that preirradiation parameter values must be included. An exemplary data format for tabulating measured parameter values is given in Table 8.10. As supplementary information to parameter data, the measurement procedure should be reported. Specifically, this includes the measurement-circuit diagram, a list of the measurement equipment and a statement regarding the accuracy and/or precision of the data.

Graphs showing the radiation-induced changes in the measured parameter values are very desirable and complement the tabulated data. The method employed for the graphical presentation of data depends on the method of data analysis and the objectives of the experiments. As a general guideline, it is recommended that parameter measurements made at only one operating point should be plotted as a function of radiation exposure. Parameters that are measured at several operating points at each fluence level

TABLE 8.8 PARTS TABULATION

Information to be Included				Useful Information					
Serial Number	Unit Designation in Test	Manufacturer	Date of Manufacture and/ or Purchase	Device Batch and Lot Number	Maximum Current Rating	Maximum Voltage Rating	Junction Area(s)	Device Application	Comments

TABLE 8.9 BIAS CONDITIONS FOR MICROCIRCUIT RADIATION EFFECTS TESTING

Type: ________

Date: ________

Test Desig	Operating Conditions On Pin																Comments
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	

TABLE 8.10 IC DISPLACEMENT EFFECTS DATA

Type: ________

Date: ________

Unit Desig	Test Desig	n/cm^2 ( ) > 10 keV ( ) 1-MeV Eq	Measurement and Test Conditions	Value	Measurement and Test Conditions	Value	Measurement and Test Conditions	Value	Measurement and Test Conditions	Value

should be plotted as a function of the parameter varied to change the operating point. The result will be a family of curves for the various radiation exposures.

Ionization-Effects Data

The measured ionization response of microcircuits should be tabulated in a fashion similar to the format described for permanent-effects data. An exemplary data format for tabulating ionizing data is given in Table 8.11. As additional useful information, consideration should be given to reporting complementary electrical-characterization data (measured before irradiation exposure) that are likely to be correlated with the radiation response.

The graphical presentation of ionization-effects data as a complement to tabulated data is very desirable. A typical format for the graphical presentation of the photoresponse as a function of ionizing-radiation dose rate is shown in Figure 8.16. For each device type on which ionizing-radiation data are reported, an illustration should show a typical response as a function of time and display the leading and trailing edges of the pulse. The dose rate at which the illustration was taken should be indicated on the photoresponse-versus-dose-rate curve. If the shape of the photoresponse changes appreciably with dose rate, additional illustrations of response should be shown, and the areas of the response curve (photoresponse versus dose rate) to which they apply should be indicated.

The results of ionization testing at two output load impedances such as shown in Figure 8.17 can be extrapolated to any arbitrary load impedance using the equivalent circuit shown in Figure 8.18. The data of Figure 8.17 when applied to the equivalent circuit yields the values for the photocurrent generator $i_{pp}(\dot{\gamma})$, and output impedance $R_{out}(\dot{\gamma})$, given in Figures 8.19 and 8.20. A similar set of measurements can be made to give the input impedance.

TABLE 8.11 IC IONIZATION EFFECTS DATA

Type: ________

Date: ________

			Rad(Si)	μs	Rad(Si)/s	(mA)				(V)			
Unit Desig	Test Desig	Thres. Def.	Dose	Nom. Pulse Width	Dose Rate	ΔI_{PS} PIN__	ΔI_{PS} PIN__	ΔI_{PS} PIN__	ΔI_{GND} PIN__	ΔV PIN__	ΔV PIN__	ΔV PIN__	ΔV PIN__

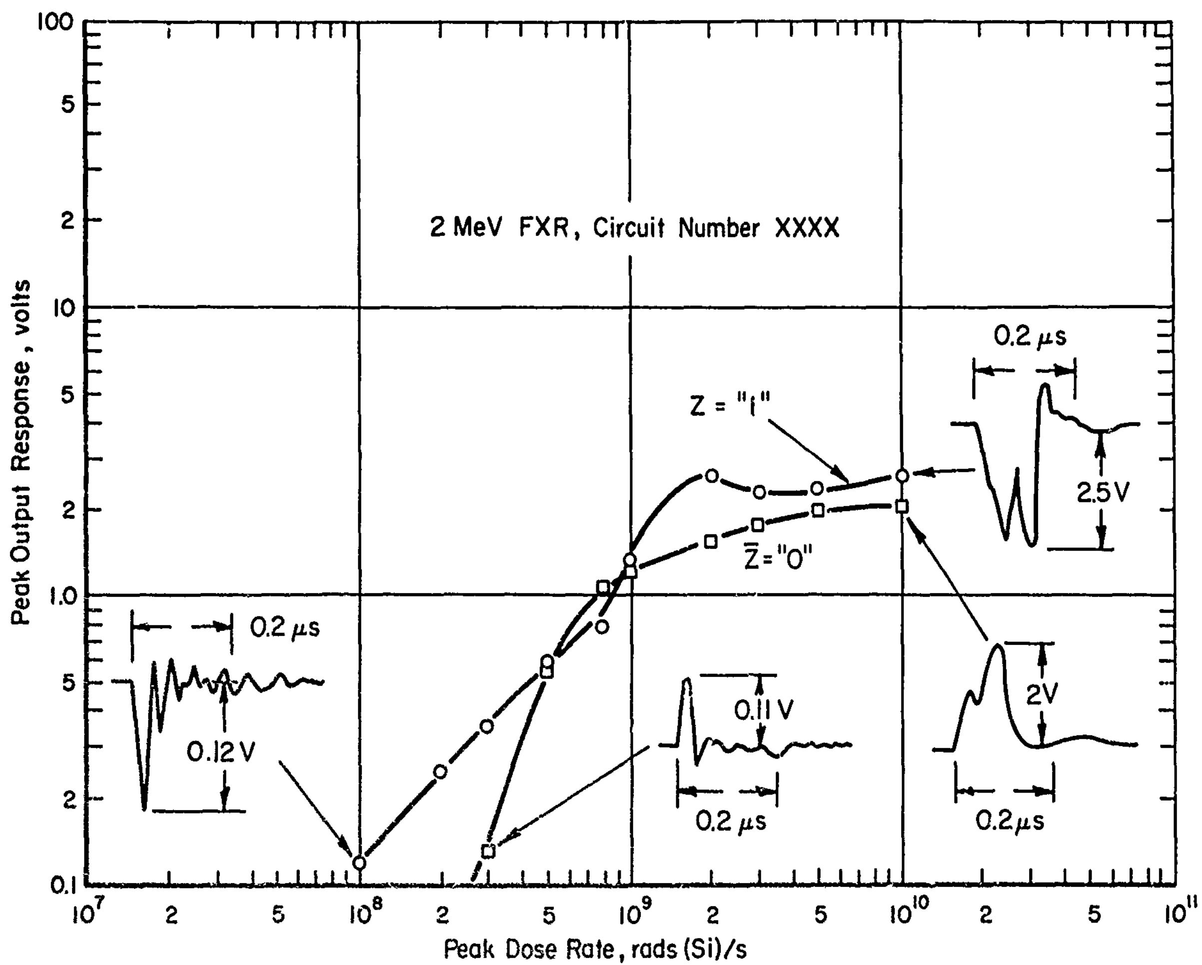


FIGURE 8. 16. EXAMPLE PLOT OF THE PHOTORESPONSE OF A MICROCIRCUIT

FIGURE 8.17. OUTPUT RESPONSE OF A LINEAR CIRCUIT TO A PULSE OF IONIZING RADIATION AS FUNCTION OF DOSE RATE FOR DIFFERENT LOAD IMPEDANCES

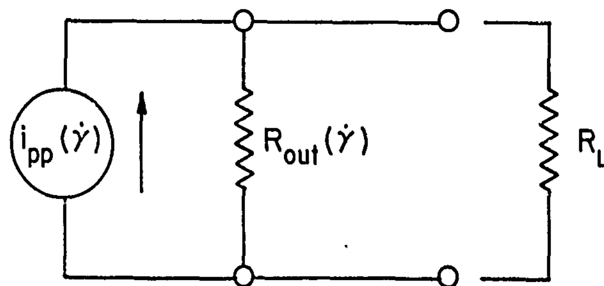


FIGURE 8.18. EQUIVALENT CIRCUIT FOR EXTRAPOLATING LOADING EFFECTS ON THE RADIATION RESPONSE

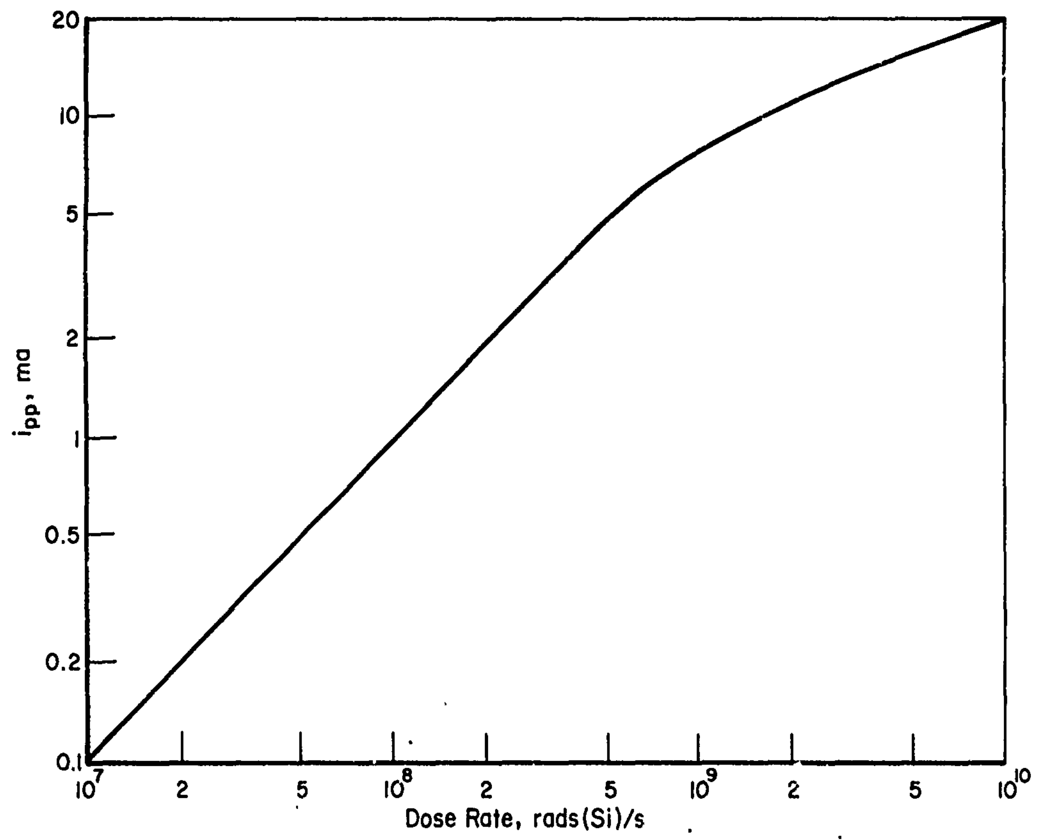


FIGURE 8.19. EQUIVALENT CIRCUIT PHOTOCURRENT GENERATOR VALUE AS A FUNCTION OF DOSE RATE

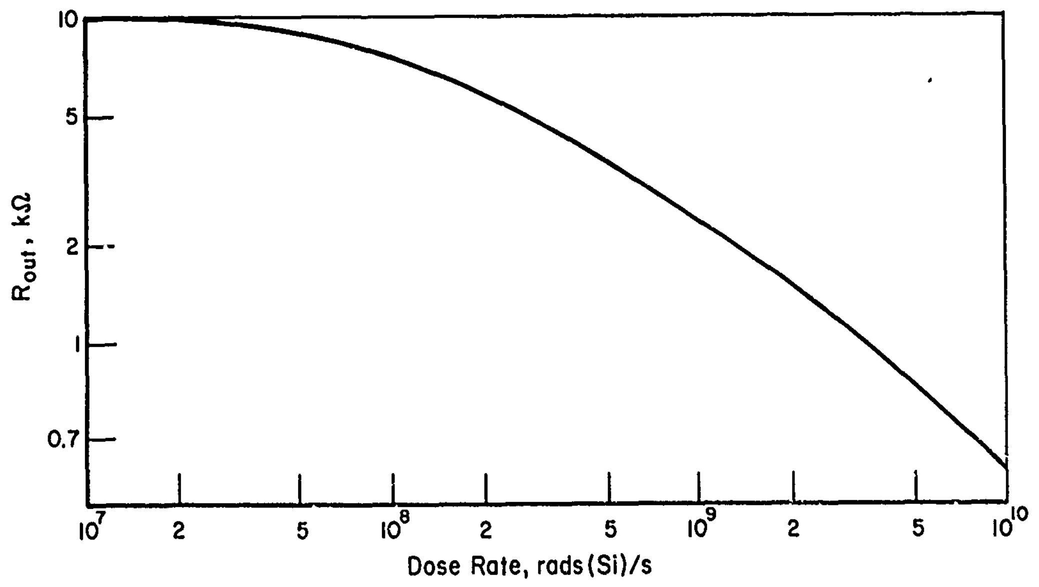


FIGURE 8.20. EQUIVALENT CIRCUIT OUTPUT IMPEDANCE AS A FUNCTION OF DOSE RATE

"Section 9.0 MSI/LSI will be mailed at a later date"

9.0

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