RADIATION EFFECTS TESTING

INTRODUCTION

Many aspects of a radiation test program must be considered to ensure that the goals of the program are met. Headaches can be avoided by a manufacturer faced with a radiation test requirement for the first time by contracting this phase of his program to a company which specializes in radiation effects. If the manufacturer anticipates enough of this type of work to warrant developing in-house capability in radiation effects, it would be beneficial to hire radiation effects experts on a consulting basis to get the program off the ground. Most radiation effects research and testing companies are willing to answer questions regarding radiation effects specifications and can provide cost estimates for test programs which permit the systems manufacturer to budget properly the cost of radiation effects testing when preparing his bid on a new system.

In a radiation effects test program, testing is conducted on three levels. Piece-part testing is designed to provide data for the circuit analyst to put into his analysis formulas to determine circuit failure and upset thresholds. Circuit- and subassembly-level testing is performed on those circuits not amenable to analysis or on those which analysis has indicated are marginal performers under spec-level radiation. Total-system-level testing is not often performed but is sometimes imposed to prove out the analysis effort and to check on any possible synergistic effects of interactions of different subassemblies.

Radiation effects testing usually consists of two types of tests;* one involves measurement of the response to a short pulse of high-energy ionizing radiation, and the other consists of evaluation of performance degradation due to permanent damage effects of exposure to a fluence of neutrons and/or a large accumulated dose of ionizing radiation.

Preliminary to the actual testing is the generation of test plans defining the facilities to be used, the measurements to be made, conditions under which the test units are to operate during irradiation, dosimetry to be used, and data-handling techniques.

FACILITY SELECTION

In selecting a facility for ionization testing, the choice between use of a flash x-ray (FXR) machine or a linear accelerator (Linac) as the ionizing radiation source is based on some of the nominal characteristics listed in Table 1.

It is obvious that, for irradiation of large assemblies, the flash x-ray with its wider coverage is the more suitable ionization source. For testing individual components or circuits which can be arranged in a small area, either facility could be used. If devices are to be tested one at a time, the Linac is the obvious choice. However, if instrumentation is available for testing a large array of small units at a flash x-ray, such testing may become economically competitive with Linac testing.

All nuclear reactors used as the source of neutrons in permanent damage testing are basically similar in that the source of neutrons is the fission process in the uranium fuel. The energy spectrum of the neutrons available to do radiation damage is, however, somewhat different at each facility due to different moderating and reflecting media associated with the reactor design. These differences in spectra must be considered when evaluating the neutron damage and when trying to relate damage by neutron fluences at different neutron facilities. This is discussed further in the section on dosimetry.

Some nuclear reactors, the "bare-critical-assembly" class of reactors, are normally lowered into a pit for shielding purposes while test equipment is set up in the exposure room, and raised into position for the actual irradiation. Another type, the so-called "swimming-pool" reactors, have the reactor core located at the bottom of a water-filled tank some 20 to 25 feet deep. The water provides shielding for personnel safety. At some facilities, this type of reactor is equipped with a "dry room," a room in which test equipment may be set up while the reactor is moved to the opposite side of the pit. When equipment is ready, the reactor is positioned against one wall of the dry room and the units irradiated. At other facilities with this type of reactor, access to it is achieved by lowering the test samples through hollow tubes to the vicinity of the reactor core.

For exposure of large-volume systems, the bare-critical assemblies or those facilities with a large dry room are most convenient; but such irradiations can be performed at the other facilities if the system is placed in a water-tight box and lowered to position beside the reactor core. For small-volume test samples, the swimming-pool reactor, where one can place samples right in the reactor core, is more convenient for high-level testing.

Accumulation of large total doses is accomplished at a Linac using either the direct electron beam or a gamma converter to generate bremsstrahlung. Another widely used radiation source for total-dose testing is the radioactive ^{60}Co isotope. There are facilities with ^{60}Co irradiators which specialize in this type of irradiation.

TEST CONSIDERATIONS

Because all irradiations take place in an exposure area from which the tester must be shielded, he is normally located 30 to 150 feet away from the units he is testing. In ionization effects testing, where the signals to be monitored are usually quite fast, this can lead to problems. Good high-frequency techniques must be used. Because of the distance between the tester and the test units, and because there is frequently a massive shield door to open and close on each entry into the exposure area, consideration must be given to the time used in making adjustments to test equipment or in changing parts. It is frequently worth the additional effort and expense to design test equipment so that it can be remotely controlled from the data station.

In designing equipment for performing radiation testing, it is important to keep in mind that the radiation can strongly interact with the test equipment itself and yield signals which are not related to the output of the device under test.

Passage of a high-energy electron beam through the circuit components under test and the test fixtures themselves can cause the ejection of low-energy secondary electrons from them. The resultant charge flow to replace these secondaries can easily be misinterpreted as an ionization signal from the device under test. Conversely, low-energy secondary electrons from the walls of the test box can be stopped in the test device and contribute to a false signal. Careful design of the test equipment can minimize these effects, and experience in such testing can provide the insight for interpreting test results even when these effects are not entirely suppressed.

Good noise suppression techniques (shielded coaxial signal lines, single-point ground, screen-room usage, line filtering, etc.) are necessary in ionization effects testing because the ionization-producing machines are horrendous noise generators. High-voltage RF generators used to accelerate the beam in Linacs cause the problems at those facilities, and the high field discharges at 10,000 to 40,000 amperes at flash x-ray facilities can cause unmanageable currents to flow in ground lines and test measurement lines.

Table 1
SOME NOMINAL FLASH X-RAY AND LINAC CHARACTERISTICS

	FXR	Linac
Pulse width (μsec)	0.02-0.1 (fixed)	0.01-8 (variable)
Pulse shape	Approx. Gaussian	Square
Peak dose rate [rad(Si)/sec]	$5x10^{11}$ - $5x10^{12}$	1-$2x10^{11}$ (short pulse small area)
Repetition rate	0.5-10/hr	Up to 720/sec
Maximum dose/pulse [rad(Si)]	$5x10^{3}$ - $2x10^{5}$	10^{4} - 10^{5}
Area covered at 5 x 10^{9} rad(Si)/sec	~1000 cm^2	~40 cm^2

***A third type of testing associated with radiation is that of electromagnetic pulse (EMP) effects. Discussions of EMP analysis and testing are beyond the scope of this article. See Interference Technology Engineers Master (ITEM) Directory and Design Guide, 1975 ed., pp. 44-49, for a comprehensive discussion of EMP.**

Active measurements during a neutron irradiation are subject to interference by the gamma field which accompanies neutron production. This ionizing radiation causes large leakage currents in devices under test and can turn on transistors which are supposed to be held off in circuit tests. Measurements on neutron degradation are best performed in stages, with electrical measurements made while the test item is out of the radiation field.

Keep in mind that items exposed to neutron irradiation become radioactive. Unless an organization has an NRC license to handle radioactive material, the exposed items cannot be returned from the test facility until the induced activity has decayed to safe handling levels. This period can range from a few days to several weeks to a few years, depending on the radiation level and the materials in the exposed test unit.

In total-dose testing, device degradation is bias-dependent so arrangements must be made to simulate application bias levels during such exposures.

DOSIMETRY

Various techniques are used to determine the dose rates and doses delivered in pulsed ionization tests. Thermoluminescent detectors (TLDs) can be used to monitor the total dose delivered in a pulse, and dividing this by a nominal pulse width yields a sort of average dose rate during the pulse. However, the TLD must be changed following each pulse.

Usually, some type of active measurement of the pulse is made, with the pulse shape being displayed on an oscilloscope. This is usually accomplished at flash x-ray facilities with a fluor and photodetector combination or with a silicon PIN. Both of these detectors are quite sensitive and cannot be used at the dose rates at which the components are tested. They are usually situated in the peripheral field and serve as pulse shape monitors only. At Linac facilities, the pulse shape is monitored as above or with a current transformer coil through which the beam passes, or with a secondary-emission monitor (SEM) which consists of a thin metal foil through which the collimated accelerator beam is passed. The electron current to this foil to replace secondary electrons knocked from it by the primary beam generates the pulse-monitoring signal. Another pulse-monitoring device used at Linacs is simply a large metal stopping block located behind the test sample in which the total beam is absorbed. The current from this block produces a signal proportional to the pulsed beam current.

The actual dose delivered at the test device location is obtained by calculations from a calibration of the observed pulse signal against measured dose at the test location. This dose measurement is made with TLDs or with calorimetric techniques. ASTM groups are currently working on dosimeter standards based on calorimetry.

At a neutron test facility, the neutron energy spectrum at various test locations has most likely been determined by the facility staff. If your test equipment is not too massive and does not contain much hydrogenous material, this measured spectrum will probably be applicable to your test. The most common technique for measuring the neutron fluence is to monitor the radiation induced in sulfur activation foils. Since these have a threshold for activation of about 3 MeV, the fluence of neutrons above this energy level is obtained from the foil reading. With this and the known spectrum, other fluence values can be obtained. Because the threshold for neutron damage in silicon is about 10 keV, the fluence of neutrons of energies greater than 10 keV is a frequently quoted measure of neutron fluence in radiation damage studies. However, since neutrons of all energies above 10 keV do not have the same damage capability, this is not the most meaningful measure to use. Another method of describing neutron fluence, in terms of equivalent 1-MeV neutron fluence, is much more valuable. Essentially, it relates the damage caused by the actual neutron spectrum used to that which would have been obtained if the sample had been irradiated with a beam of 1-MeV monoenergetic neutrons. The method of doing this is beyond the scope of this document.

Total-dose measurements are usually done using TLDs or cobalt glass or silver-phosphate glass dosimeters. When total dose is being delivered with a Linac, it is possible to establish a measure of dose per pulse and monitor the number of pulses to determine total dose.

TEST MEASUREMENTS

In ionization effects tests, the measurements to be made are all transients. The ionizing radiation pulse generates electron-hole pairs throughout the material being irradiated, and the effects of these on the test devices are measured. The primary effect of ionization is to cause leakage across reverse-biased p-n junctions. In tests of transistors, the leakage current across the reverse-biased collector-base junction with the emitter open is the parameter of primary interest. This is reported as either primary photocurrent (I_{pp}) versus dose rate ($\dot{\gamma}$) or as primary photocharge (Q_{pp}) versus dose (γ) with an added notation of the device recovery time (τ). The most complete characterization of the effect of an ionization pulse on a transistor would list the peak photocurrent, the total photocharge transferred, the recovery time, the dose, and the radiation pulse width. To characterize the ionization response of a transistor, these data should be recorded for a number of dose rates covering the range from about 10^7 to 10^{11} rad(Si)/sec. Five data points are recommended, and three is the minimum number. A diode is tested in exactly the same manner with the same data requirements.

Integrated circuits must be treated as "blackboxes" in ionization testing because only input, output, and bias point terminals are usually available for monitoring. Digital circuits are tested in both logic states with loads simulating those seen in actual use. Usually, the important measurements are the threshold radiation levels, the output transients, and the power supply current transient at maximum dose rate. Threshold is a rather arbitrary value, but is usually defined as the radiation level that induces a transient on the output which could be interpreted as a change in logic state. Linear devices usually show a linear response to radiation over some range of dose rate, so a set of dose-rate data is required to characterize the response. Again, output levels at maximum dose rate should be inspected to obtain a measure of device recovery time, and power supply transients are monitored to ascertain peak current drain at maximum dose rate.

Analysis of circuits provides information on the points in the circuit to be monitored to provide the most useful data on circuit response to an irradiation pulse. The more complex the circuit, the more difficult it becomes to relate the radiation effects data to what is actually happening in the circuit. At the subsystem level, measurements are restricted primarily to those points which interface with other subassemblies. System tests normally consist of low-level "operate through" tests and higher-level "survive" exposures.

In permanent damage testing of piece parts, the number and type of parameter measurements to be made depend on the equipment available to make the measurements and the circuit application of the device being tested. If an automatic semiconductor tester is available, all parameters for which there are manufacturers' specifications can be measured at a number of operating points. If an automatic tester is not available, those parameters considered crucial in the circuit application of the device must be measured with the realization that a later application of this same device in another operating mode may call for additional testing.

DEFINITIONS OF SPECIALIZED TERMS

Dose - A measure of energy deposited in a given material by exposure to ionizing radiation. Unit, rad(material).

Flux - The flow of particles per unit time through an imaginary sphere of unit cross-sectional area. Units, n/cm^2-sec, e/cm^2-sec, p/cm^2-sec, etc.

Fluence - The number of particles that enter an imaginary sphere of unit cross-sectional area; integrated flux. Units, n/cm^2, e/cm^2, p/cm^2, etc.

Rad - The unit for measuring dose; equal to 100 erg/g. This unit must always specify the material referred to — e.g., rad(Si) for dose deposited in silicon.

Bremsstrahlung - German for "radiation resulting from a stopping process" or "braking radiation." This is the electromagnetic radiation produced when a beam of charged particles is stopped in a target material. The bremsstrahlung spectrum is continuous from zero to the maximum energy of the incident particles.

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