SECTION 19. RADIATION TESTING

19.1. INTRODUCTION

The sensitivity of semiconductor devices to radiation is often very variable and it is therefore impossible to use theory alone to predict the effect on a device of a given exposure to radiation. Actual irradiation tests must then be an integral part of the evaluation of a device and, sometimes, tests must be performed on each batch of devices. A large number of device radiation test programmes has been performed in Europe and an even larger number in the USA. The simulation of space radiation effects in the laboratory is quite difficult to achieve and the results thereof are often not those expected during planning.

This section is aimed at providing support in the design of adequate test programmes. It reviews:

- the main radiation sources which may be used together with their advantages and disadvantages and
- the main types of measurement which can be made, together with suitable implementation methods.

Reference is also made to the standard test procedures developed in the USA and Europe.

19.2. RADIATION SOURCES

19.2.1. Simulation of space radiation

The differences between radiation conditions in space and their simulation in the laboratory are frequently quite large. The incident space irradiation consists of a complex, mixed particle environment which, as discussed earlier, is altered and made even more complex by passage through spacecraft enclosures. The dose is delivered steadily over a long period of time - often, several years. Short-term variations in dose rate by up to 11/2 orders of magnitude may be experienced, depending on the orbit. Most of the time, one can only obtain radiation beams at a number of discrete energies and often it is also difficult to modify the rate at which the machine will deliver the radiation. Bearing these facts in mind, one must therefore modify the raw short-term results of "simulation" tests when converting them into predictions of space radiation conditions. One may also wish to monitor the irradiated device at intervals of minutes, days and months and introduce factors to allow for qualitative differences in space and laboratory radiation as well as the "dose rate effects" discussed in earlier sections.

Despite the above mentioned problems, a surprisingly wide range of devices can be tested suitably by the use of high-activity gamma-ray-emitting isotopes, e.g. the well-known cobalt-60 hot cell or "irradiator". However, one must always classify carefully the physics of the effect one is aiming to simulate - whether it is classed as a total-dose ionisation effect, permanent bulk damage effect single-event upset or a transient effect of some other kind.

19.2.2. Gamma-rays

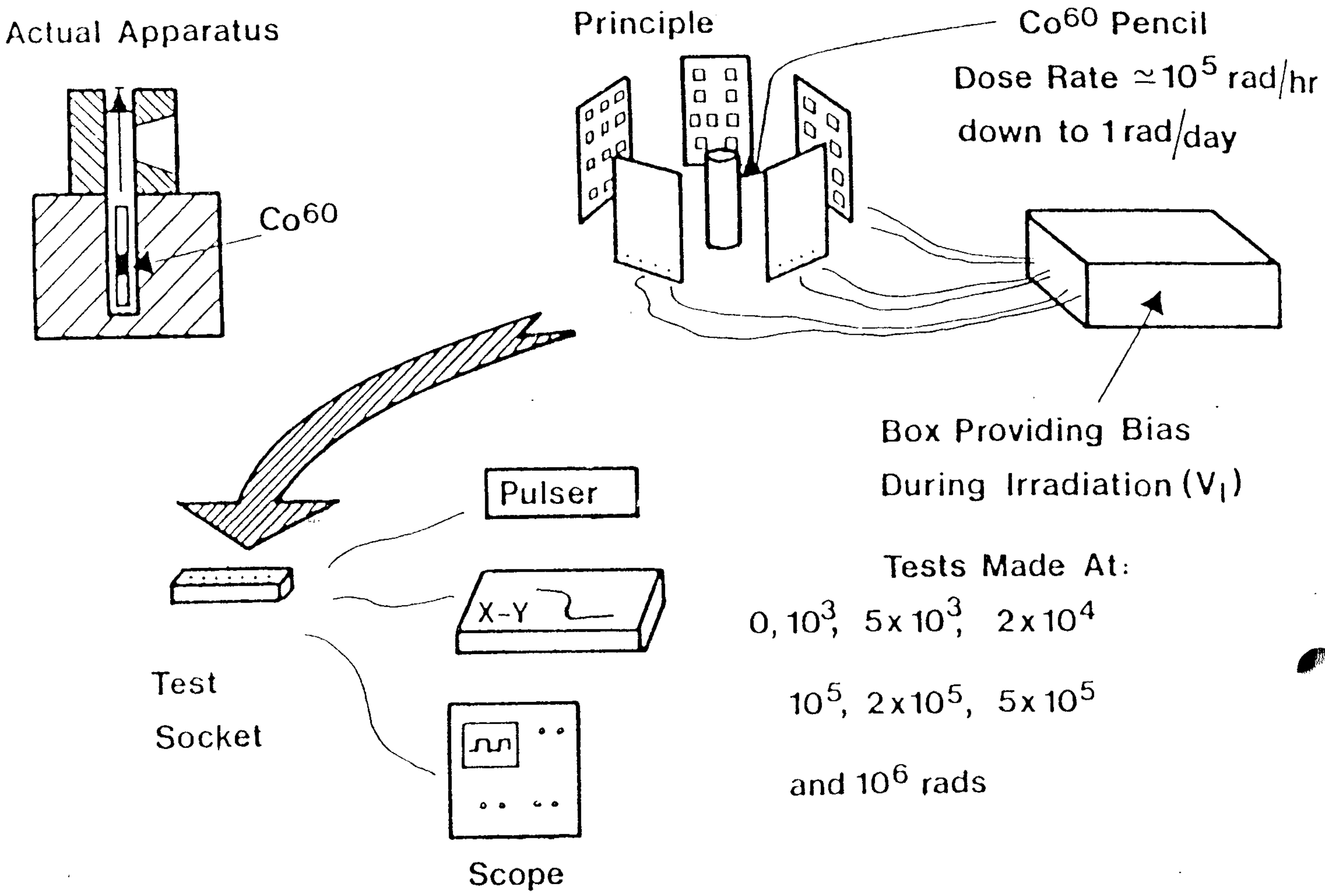
The source most commonly used for simulation of ionisation effects on silicon components or materials is Co-60 which emits photons of energy 1.173226 and 1.332483 MeV and has a half-life of 5.27 years. It is utilised for industrial irradiation, sterilisation, radiotherapy and biological research; well-designed irradiators are therefore widely distributed geographically. Several standard commercial irradiation cells are on the market and contract irradiation facilities are often available. It has been amply proven that ionisation due to gamma rays provides a useful simulation of the penetrating electrons and protons in the space radiation spectrum. For all practical purposes, a rad(Si) deposited by gamma-rays produces the same quantitative response in SiO_2 films with respect to charge-trapping and interface state creation as do space protons, electrons and bremsstrahlung.

Cobalt-60 is produced from inactive Co-59 by heavy neutron irradiation in a reactor. In a typical irradiator, a cylinder of cobalt-60 is sealed in a steel jacket and placed in a thick lead shield or concrete cell. A large number of electronic samples, arrayed in sockets in circuit boards, can be placed near the source and their response to the radiation can be monitored continuously by means of wires leading out of the cell. In some commercial irradiators, designed for the irradiation of chemicals or animals, the whole exposure takes place in an enclosed structure which can thus stand freely in the corner of the laboratory. Because gamma rays are so penetrating, circuit boards can be stacked. A source of medium strength will have an activity of about 1 000 curies (3.7×10^{13} becquerel).

Some typical configurations and dose rates are shown in Figures 19.1 and 19.2. Given a cell several metres in length, it can be seen that dose rates can be varied from over 10^5 rads.hr^{-1} (allowing the accumulation of mission doses in under an hour) to, say, 100 rad.hr^{-1}. The latter rate is only about 30 times a typical space dose rate (a high-radiation orbit may average 2×10^5 rad per 10 years or about 3.rad hr^{-1}) and, if real-time conditions are desired, shielding by a few centimetres of lead can produce a further reduction. Alternatively, a source of lower activity can be used at a closer distance. ESA has supported the development of one such low-rate irradiation facility - named LORAD - at Harwell, U.K. (see Hardman et al, 1985).

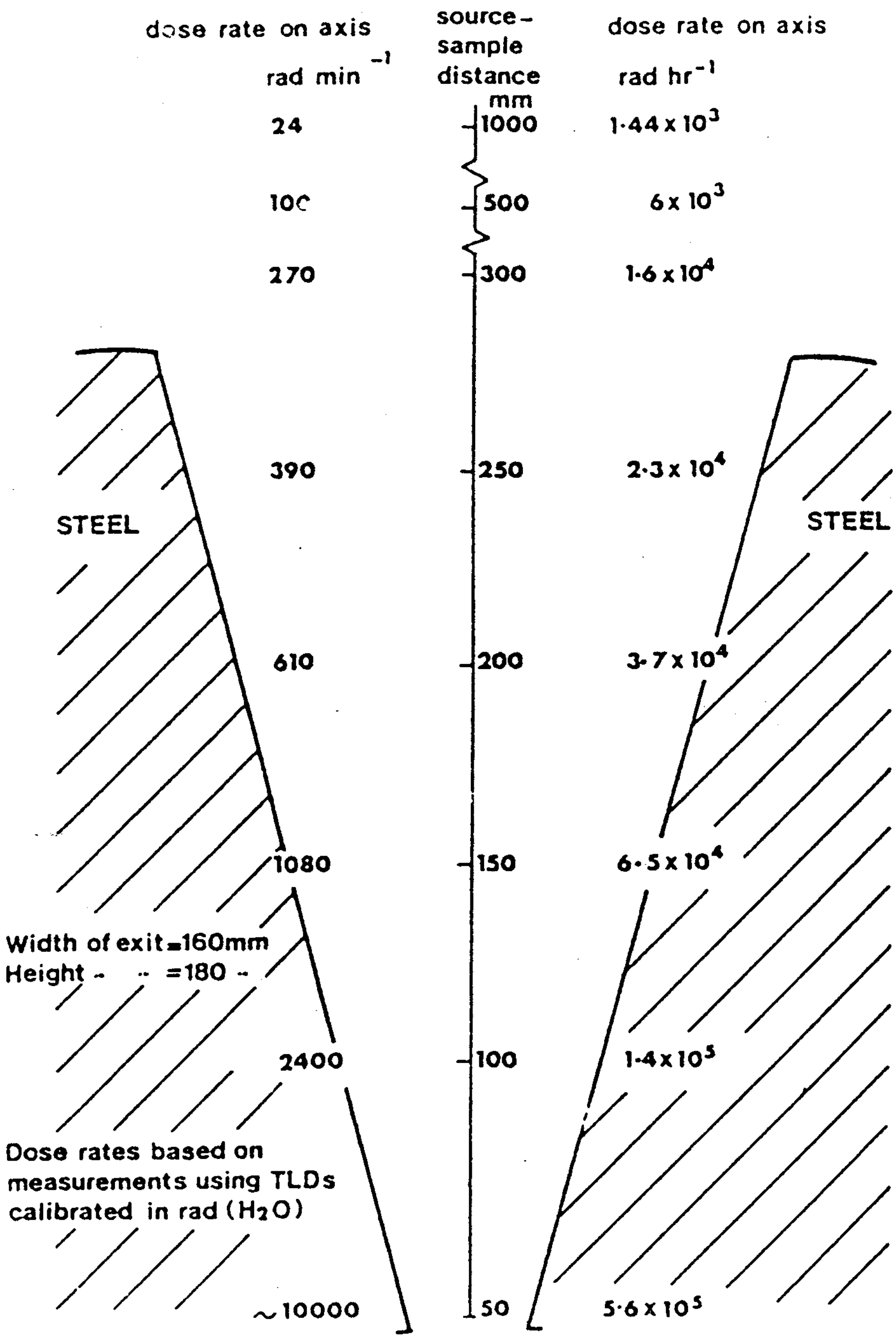
The medium-strength sources described above will cost about 20000 U.S. Dollars for the free-standing cell structure with automatic positioning of the isotope for timed exposures. The purchaser then has freedom to instal the optimum amount of isotope at a price of a few U.S. Dollars per curie.

Another isotope source which has been adopted widely as a practical irradiator is caesium-137. This emits 0.6 MeV gamma rays and has a half life of about 30 years.



Typical arrangement for testing with Co-60 gamma rays.

FIGURE 19.1 - GAMMA-RAY TESTING



Cross-section of steel jaws of Co-60 Cave, with dose rates corresponding to position on axis. Doses are in rad (water). Activity approx. 1000 curies

FIGURE 19.2 - GAMMA-RAY TESTING

19.2.3. X-rays

Like gamma-rays, X-rays will simulate the space environment by inducing ionisation. Even low-energy X-rays, provided they can be introduced into the active region of the device and the doses correctly estimated, can be effective. They were first used on oxide-passivated devices by the staff of Bendix and RCA. The tube voltages were 150 and 250 keV respectively. The response of devices was found to be identical to that given by 1 MeV and 125 keV electrons as long as the base widths of the transistors were low enough to prevent interference from bulk damage. The same conclusion was reached with respect to an 85 keV radiographic X-ray set (23) over a wide range of bipolar and CMOS devices. ESTEC has routinely measured device responses in a 150 kV radiographic set (Adams et al). Careful dosimetry of a 320 kV X-ray set has been performed, using actual CMOS circuits as a cross-reference (Kelliher et al, 1985).

X-rays are generated when a beam of electrons bombards a target, usually of a high-Z metal such as tungsten or copper. For high beam currents, the target must be cooled; the power supply is large in size if high beam currents are desired. The electron beam, colliding with the target, excites a "white spectrum" of bremsstrahlung X-rays (actually peaked broadly at about half the beam energy), upon which the K and L peak emissions of the target metal are superimposed. For tungsten, the main peak is 59.3 keV (K) and for copper 8.04 keV (K). The L peak for tungsten is 8.396 keV. It is normally desirable to filter out these and also the lower-energy white radiation so as to avoid too much influence of the encapsulation on the dose penetrating to the active silicon device. However, one specialised wafer irradiator uses unfiltered tungsten radiation (Fleetwood et al, 1985). Dose rates at 10 mA in the 150 kV ESTEC source (tungsten X-rays) are approximately 10^3 rad.min^{-1} at a distance of 330 mm and about 10^2 rad.min^{-1} at 860 mm. The attenuation of this beam by a 0.3 mm Kovar lid is about threefold.

The use of X-rays requires care, but can be recommended for identification of sensitive technologies and the irradiation of limited numbers of devices. The main advantages are the low cost and wide distribution of X-ray equipment and the high safety standards available in X-ray equipment. The care required concerns the accurate administration of dose. In order to produce repeatable penetration power in an X-ray beam, the power-supply voltage and tube current must be stable. The ESTEC facility has line-voltage compensation of ~40V. The degree of filtration must be kept constant because this controls the X-ray photon energy spectrum. Both the degree of package penetration and the response of dosimetry are very sensitive to changes in energy spectrum.

Unlike gamma isotope facilities, X-irradiation methods have not yet been standardised. In view of the limited cone angle and relatively high absorption coefficient of kilovolt X-rays, isotope sources are preferred for bulky equipment, large part throughput and high-accuracy experiments.

TABLE 19(1) - TYPICAL FACTORS FOR CONVERTING ELECTRON FLUX TO DOSE

CGS units	Beam diameter 1.13 cm Area 1 cm^2	Beam diameter 2 cm Area 3.14 cm^2	Beam current
Flux ($cm^{-2}s^{-1}$) Dose rate (rad(Si) s^{-1})	6.2×10^{10} 2.07×10^3	1.97×10^{10} 6.57×10^2	10 nA
Flux ($cm^{-2}s^{-1}$) Dose rate (rad(Si) s^{-1})	6.2×10^{13} 2.07×10^6	1.97×10^{13} 6.57×10^5	10 A
MKS units	Beam diameter 0.013 m Area $10^{-4}m^2$	Beam diameter 0.02 m Area $3.14 \times 10^{-4}m^2$	Beam current
Flux ($cm^{-2}s^{-1}$) Dose rate (gray(Si) s^{-1})	6.2×10^{14} 20.7	1.97×10^{14} 6.57	10 nA
Flux ($cm^{-2}s^{-1}$) Dose rate (gray(Si) s^{-1})	6.2×10^{17} 2.07×10^4	1.97×10^{17} 6.57×10^3	10 A

For 1 MeV electrons incident normally, and with no cover on device (3×10^7 cm^2 = 1 rad(Si))

19.2.4. Electrons

All electron beams act as a source of ionisation, but only the high-energy machines (particles of energy considerably greater than 0.1 MeV) will produce displacement damage in semiconductors.

Consequently, one of the most generally useful sources is the Van de Graaff generator, especially because this machine can be designed to operate at any particle energy between 0.1 and 5 MeV.

An electron beam is accelerated by the field between earth (the target) and an electrode charged to a very high static potential. The charging is accomplished by means of a moving belt which carries charge from a d.c. generator to the insulated "head" electrode. Potentials of 5 million volts can be produced, but with the more common machines, 1 million volts is the limit. Electrons released in the head are accelerated away from it down an evacuated column and emerge through a titanium vacuum window as a beam of about 2 cm diameter. Devices can be placed in this beam. At 1 MeV, the electrons can travel several centimetres in air without great loss in energy, so that irradiation can be performed in air. Typical device encapsulation (e.g. 0.3 mm Kovar IC lids) extracts energy and scatters 1 MeV electrons heavily. Consequently, there is always uncertainty about the dose received at the chip of an encapsulated device. Some engineers object to removing the encapsulation for the purposes of testing. The dose rate can be varied by altering beam current and beam focus or sweeping the beam. Beam current can often be varied from 10 nA to 10 μA which, in a 20 mm diameter beam, yields particle fluxes from about 2×10^{10} $cm^{-2}.s^{-1}$ to 2×10^{13} $cm^{-2}.s^{-1}$. These fluxes correspond to dose rates from about 600 to 600 000 $rad.s^{-1}$.

Table 19(1) gives the conversion factors. Since the dose rates in space are in the range 10^{-5} to 10^{-3} $rad.s^{-1}$, the acceleration of test rate here is over 10^6 times. In many cases, this is acceptable, but it is inconvenient that, because beam currents cannot be controlled below a few nanoamperes, the dose rate cannot be lowered further.

Resonant-transformer accelerators yield electron-beam currents up to 1 mA in the 1 to 3 MeV range. Since the peak annual fluences encountered in space with $E > 0.5$ MeV are 3×10^{14} cm^{-2}, it can be seen that test runs need only a few minutes for actual irradiation.

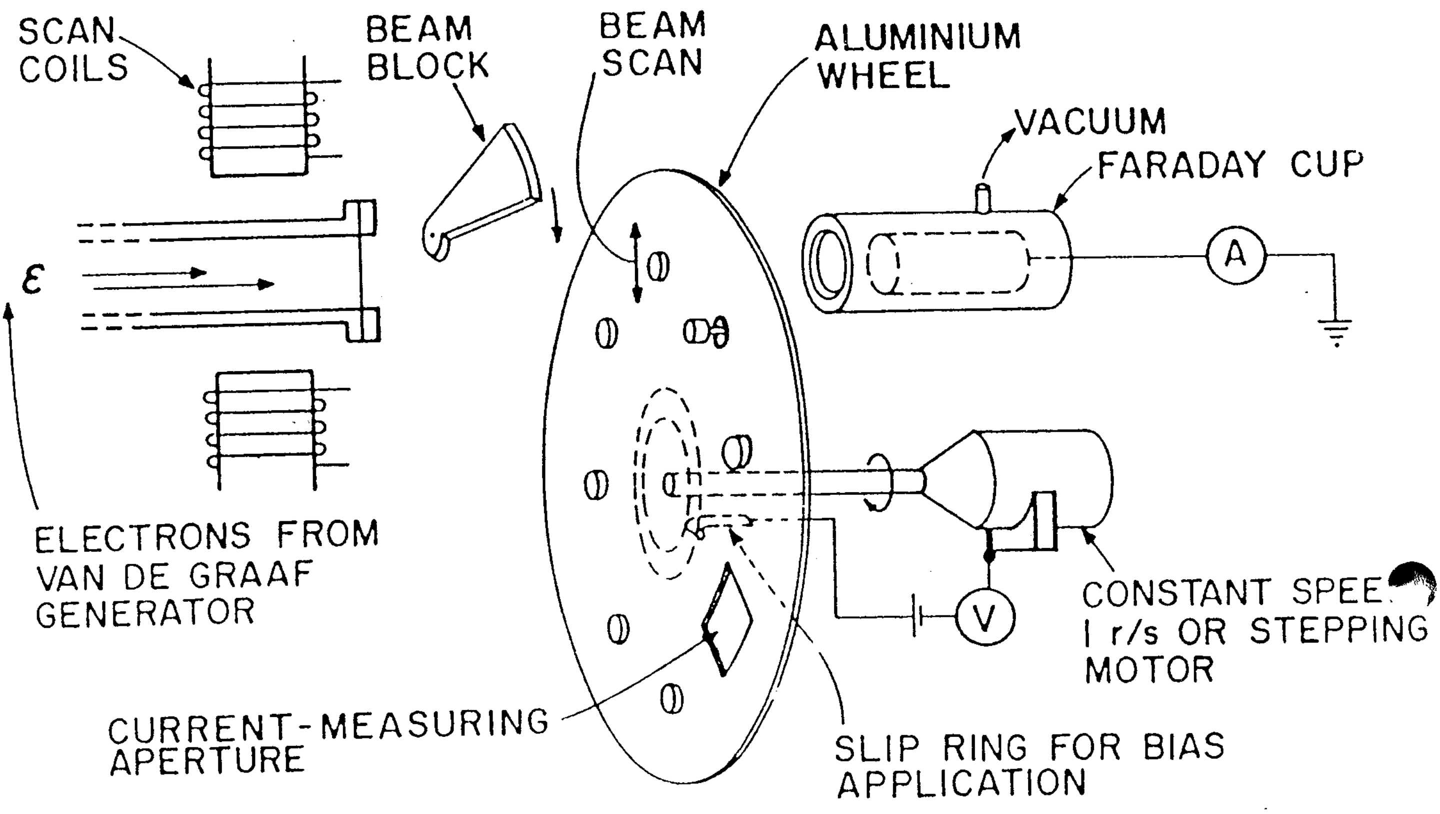
A linear accelerator (LINAC) provides electrons of higher energies, typically 4 to 40 MeV in rapid, square pulses. Electrons fired from an electron gun in a waveguide can pick up RF energy and be accelerated from a few keV to several MeV. Average currents are again the microampere range, but instantaneous dose rates can be as high as 10^{10} $rad.s^{-1}$.

A typical experimental arrangement such as would be used for any high-energy electron (or proton) beam exposure is shown in Figure 19.3. It was developed at RCA for solar cells; using a 1 MeV Van de Graaff generator, it gives very high dose uniformity. Scanning of an array of samples can be achieved magnetically, thus avoiding movement of the samples, and it has been shown that doses can be administered in this way with suitable accuracy. However, owing to the pulsed nature of the irradiation, other workers prefer to use a scattering foil to spread the beam.

In view of the price of an electron accelerator in the 0.5 to 3 MeV range (between 100 000 and 300 000 U.S. Dollars), the need to maintain a vacuum system, a large power supply and control circuits and the cost involved in servicing the pressurised insulated column, it would be impracticable to dedicate such a machine to space radiation testing use.

Another source of electrons of interest for special experiments on low dose rates is the isotope Sr-90/Y-90. It emits beta rays over a spectrum not dissimilar to that encounted in near-Earth space. Rates can be achieved such that a typical 1-year dose can be accumulated in several months, i.e. the acceleration factor is less than 10. Such a source is used at DERTS, Toulouse (F), for low-dose rate experiments on MOS devices.

Unfocussed beams of electrons in the kV range are easy to form with a kV power supply and a simple electron gun (television tube or "home-made" gun). Such beams can be used to irradiate thin films and beam currents of milliamperes can be obtained. One type of kV beam, which is of lower current but of much higher precision, is that used in the Scanning Electron Microscope (SEM) (see Galloway). Typical energy is 35 keV and the beam can be precisely aimed and scanned over a selected microscopic area of a semiconductor device (uncapped, of course). Currents are usually in the nanoampere range, but the irradiated area can be as small as a tenth of a micrometre square. Thus, the local dose can be made very high (many megarads per second). If the beam is rastered over the whole of the chip, dose rates as low as a few kilorads per second may be achieved.



Typical arrangement for 1 MeV electron radiation testing

FIGURE 19.3 - ELECTRON BEAM TESTING

The SEM method is worthy of consideration because the beam is already used in the imaging mode for quality control inspection of semiconductor chips at low dose levels. The opportunity of adding a "sacrificial" high-dose irradiation on a selected area of the chip is therefore an economical complement to the usual inspection. The problem is dosimetry because the precise thickness of the "passivation" on wafers is not always known.

19.2.5. Protons

This section deals mainly with the displacement damage induced by protons in encapsulated silicon components. Only proton energies above 15 MeV, for which the range is 0.060" or 1.524 mm Al, need concern us. For surface coatings, energies down to 1 keV are vital and special facilities are available at ESTEC for their exposure . Recent work of imaging CCD's has shown that these are sensitive to low energy proton displacement damage requiring irradiation facilities between 0.5 MeV and 200 MeV.

For acceleration of protons to energies above 15 MeV, the most common machine is the cyclotron. In this instrument, high-frequency currents applied to two D-shaped electromagnets, supply energy to a beam of hydrogen ions injected into a circular "race track". The trajectory of the particles is an outward spiral and particles can be picked off at an exit tube. A typical maximum energy for a nuclear research cyclotron would be 20 MeV and fluxes of the order of 10^{13} cm^{-2} .hr^{-1} are achieved. As the damage efficiency of protons in silicon falls off sharply with energy, 20 MeV is very suitable for devices. The spectrum in space penetrating a compartment will be richest in this energy range, lower energies being attenuated greatly by the intervening absorber.

Useful work has been done with protons at 10 MeV (Boeing), 100 MeV (McGill University), 16.8 MeV (Princeton University) and at 22 and 40 MeV (NASA Langley). In Europe, some work has been done in the 7 to 50 and 200 to 3000 MeV ranges. Experiments on solar cells and bulk silicon have been used to construct the "BGR" curves mentioned earlier.

Since the annual proton fluences (E > 15 MeV) for the reference missions discussed previously are, at most, 10^{11} cm^{-2} (EXOSAT received 1.11 x 10^{10} cm^{-2} in 2 years), the fluences required for testing can be built up on a cyclotron in a fraction of an hour. Even at the peak of the proton belt, annual fluences (E > 10 MeV) are about 10^{13} cm^{-2}.

Most Van de Graaff machines can be converted for accelerating protons by reversing polarity and supplying a source of ionised hydrogen at the head. On some modern machines in the 0.5 to 3 MeV range, this conversion is effected with ease.

Other sources of high-energy protons occasionally available for irradiation are proton linear accelerators operating in the 10 to 100 MeV range and cyclotrons operating up to 800 MeV.

Very recently proton nuclear interactions have become important for single event upset and latchup in complex devices. Some modern integrated-circuit technologies are sensitive to the ionisation from nuclear reaction products. Significant risk exists for low Earth-orbiting satellites passing through the South Atlantic Anomaly (see Section 3). In order to study these, and other, proton effects ESA has sponsored the development of a Space Proton Irradiation Facility at the Paul Scherrer Institute, Villigen, Switzerland. This facility can be used to simulate continuous spectra (e.g. South Atlantic anomaly or Solar Flare) from 10 to 300 MeV. This is achieved by moving degraders in and out of the beam under computer control. An X-Y scanning system, also computer controlled, allows irradiation of an area 10 x 10 cm with high uniformity. Mono-energetic irradiations may also be carried out up to 590 MeV.

19.2.6. Neutrons

Although neutrons are not found in significant numbers in space, their bulk defect structures have a family resemblance to those produced by higher-energy protons and electrons. Also, a very large amount of nuclear-reactor testing has been performed in military programmes. Materials test reactors, which possess beam tubes or hydraulic tubes ("rabbits") or have a swimming-pool design, can be used for the exposure of samples to fast neutrons.

Neutrons are generated by the fission of uranium-235 and have energies spread over the range 0.1 to 3 MeV ("fission spectrum"). However, if the flux of neutrons is allowed to collide with the moderator material or coolant, the neutron energies are reduced to thermal energy of the order of 0.025 eV). This is undesirable for device irradiation because neutrons of energy below 10 keV yield few displacements. Moreover, they can be captured by the device materials, particularly gold and silicon, and produce radioactivity (the devices emerge "hot") and an inappropriate type of damage. Omnidirectional fast-neutron fluxes in reactor cores are usually well above 10^{15} cm^{-2} $.hr^{-1}$. They are accompanied by isotope gamma ray doses of the order of 10^6 $rad.hr^{-1}$, which complicates the interpretation of responses.

Beams of 14 MeV neutrons from the fusion of deuterium and tritium ions, colliding at a few keV, can be produced in either electrostatic machines, which accelerate deuteron beams at 200 keV, or in various experimental plasma generators.

19.2.7. UV photon beams and other advanced oxide injection methods

Vacuum Ultraviolet (VUV) light gives, qualitatively, exactly the same type of charge build-up as high-energy radiation. However, the method at present is a research technique suitable mainly for characterising oxide film technology at the wafer stage. The same comments apply to avalanche injection techniques in which a controlled avalanche breakdown in the semiconductor injects hot electrons or holes into the oxide film. The difficulty is in control, dosimetry and interpretation. A third advanced method, not so well characterised, is the application of corona discharge to a bare oxide.

19.3. COSMIC RAY UPSET SIMULATION - HEAVY IONS

Single-Event Upset (SEU) simulation requires a source of energetic heavy ions with Linear Energy Transfer (LET) values ranging from about 1 MeV/mg/cm^2 to about 45 MeV/mg/cm^2. While the lower LET values are used to investigate the behaviour of a device around threshold LET, the higher values are used to establish the limiting cross-section or saturated error rate (see later). Table 19(2) gives a range of commonly used ions and their LET in silicon.

The machine used most frequently for SEU testing is the cyclotron, at accelerating potentials of up to 300 MeV, and with a range of gaseous ion sources such as krypton, argon, oxygen and neon. The device to be tested is mounted in an evacuated target chamber which contains silicon detectors and a Faraday cup for beam-monitoring and has feed-throughs for electrical connection. In general, provision is made for the device to be tilted with respect to the beam so as to allow the path-length of the ion through the device to be varied.

Cyclotrons for SEU testing include the 88-inch machine of the University of California at Berkeley (used by JPL and Aerospace groups) and the "ALICE" at IPN, Orsay (used by CNES, ESA and Harwell groups).

Although somewhat limited with respect to the maximum LET achievable, the Tandem Electrostatic Generator is also a suitable source of heavy ions. This generator is a special form of the Van de Graaff design. The accelerating electrode within the Tandem is half-way down the column and charged to a positive potential.

TABLE 19(2) - LINEAR ENERGY TRANSFER OF IONS COMMMONLY USED FOR SINGLE-EVENT-UPSET TESTING

NUCLIDE	ENERGY (MeV)	ENERGY/ NUCLEON (MeV/μm)	LET (SI) (MeV/mg/cm^2)
7 Li	15	2.10	0.6
12 C	35	2.92	1.0
20 Ne	150	7.50	2.9
16 O	21	1.31	4.0
20 Ne	46	2.30	6.4
40 Ar	300	7.50	7.5
40 Ar	150	3.75	11.0
35 Cl	35	1.00	15.0
56 Fe	400	7.14	18.0
56 Fe	300	5.36	20.0
56 Fe	150	2.68	23.0
84 Kr	60	0.71	27.0
84 Kr	150	1.79	35.0
129 Xe	81	0.63	40.0
241 A (alpha source)		-	0.6
252 Cf (fission fragment source)		-	43.0

The ion source produces negative ions which are attracted by and accelerated towards the electrode. On nearing the electrode, they are stripped of their charge by foils to a positive charge stage and accelerated away from it towards the mass analyser and the target beam line. The Tandem produces two stages of acceleration and because the positive charge state can be quite high (e.g. Oxygen: +5), the overall acceleration energy may be several times the terminal voltage of the machine. The Tandem Generator at AERE, Harwell, has an LET range of about 0.5 to 37 MeV/mg/cm^2 and has been used successfully by the ESA/Harwell group for its investigation into threshold response.

A development in SEU testing by AERE and ESA is the use of fission products from a small radioactive source (1 microcurie of californium 252) for the production of upsets. The mean LET of the fission products is 43 MeV/mg/cm^2 which, in general, is sufficiently high to enable the limiting cross-section to be established. The LET can be degraded by the use of foils or atmospheric gases, but only to about 15 to 20 MeV/mg/cm^2; this is not low enough to permit the threshold of most of the modern technologies to be determined. The range of the fission particles is 15 μm in silicon and this should be taken into account, particularly for latchup testing.

The main advantages of the "CASE" system (Californium Assessment of Single-Event Effects) are its low cost, simplicity and flexibility. The entire test facility is contained within a simple bell jar and, provided the normal precautions for the handling of radioactive sources are taken, may be used in any laboratory. The system may be interfaced with any test equipment and used for extended periods to accumulate good SEU statistics. Figures 19.4 and 19.5 show schematics of cyclotron/Tandem and "CASE" test configurations and Table 19(3) gives the nuclear characteristics of the Californium 252 source.

TABLE 19(3) - NUCLEAR CHARACTERISTICS OF A CALIFORNIUM 252 SOURCE

Californium 252	: 1 microcurie source
Half-life	: 2.65 years
Neutron emission	: 4 x 10^3 n/s (average energy 2 MeV)
Neutron dose rate	: 0.023 mrem/hr at 1 m
Alpha particle emission	: 3.1 x 10^4 particles/s
Energy range	: 5.975 - 6.119 Mev
Fission fragment emission	: 10^3 particles/s (energy distribution peaks at 80 and 104 MeV)
Gamma exposure rate	: 0.002 mR/hr at 1 m

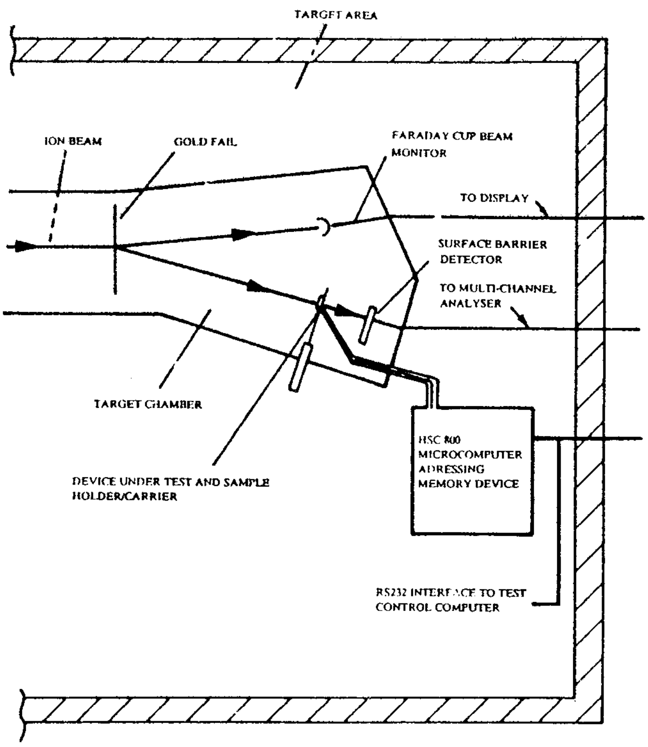


FIGURE 19.4 - CYCLOTRON ACCELERATOR TEST CONFIGURATION

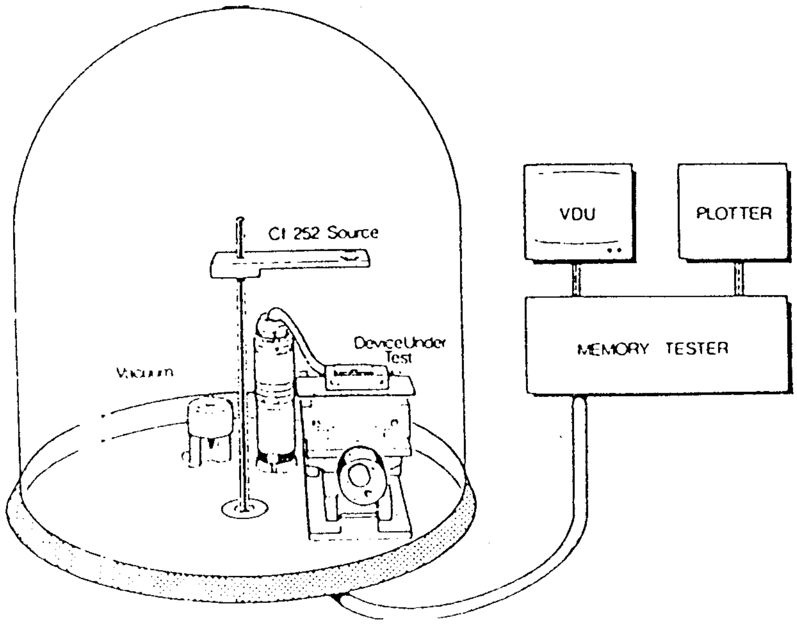


FIGURE 19.5 - "CASE" TEST CONFIGURATION

19.4. SUMMARY OF RADIATION SOURCES

In summary, the desirable features of radiation test sources for semiconductor devices are:

- Easy access (for "in situ" access and rapid sample change),
- Large area of beam (for large sample throughput),
- Highly penetrating radiation (avoids encapsulation problem)
- Unambiguous dosimetry,
- High stability (reduces dosimetry),
- Safety in operation,
- Low capital cost,
- Repeatability of doses from one facility to another,
- Flexibility in dose rate.

As isotope sources rate highly in all of the above criteria and cover a very wide range of the space radiation tests required for electronic and optical devices, their universal acceptance as standard radiation sources for total-dose ionisation effects is envisaged. In a number of cases, bulk displacement damage may be important (e.g. solar cells, thyristors) and here particle irradiation is essential. Single event upsets constitute another special group which requires particles to have the correct LET value and adequate range.

19.5. DOSIMETRY

19.5.1. General

Dosimetry is the process of measuring the amount of radiation to which a sample is exposed in a given radiation beam. It is also taken here to cover the measurement of particle or photon fluxes and of the absorption or deposition of energy in the radiation-sensitive sample of interest, usually silicon or silicon dioxide, but possibly plastic or optical material. Dosimetry grew up in the fields of radiobiology and medicine, where only energy deposition in the form of ionisation is of interest and takes place primarily in the aqueous or organic media of living tissue.

Thus, dosimetry methods and concepts have been developed mainly for the calculation of ionisation in carbon (organic materials), water and air (the medium used in ionisation gauges). We, on the other hand, are involved in the field of semiconductor components and are interested mainly in the deposition of ionisation energy in silicon oxide and silicon as well as the deposition of energy in the form of atomic displacements in lattices. Thus, space radiation covers certain fields not found in the dosimetry textbooks.

19.5.2. Definition and use of radiation units

Until recently, the gas ionisation chamber was the only means to measure electrically the dose derived from a radiation beam. This chamber is merely a pair of electrodes arranged to collect the air ions created in a certain volume, but the values thus measured still serve as a standard to which to relate other units and form the basis on which the Roentgen unit has been defined. The latter is that unit of exposure to radiation which creates air ions to the level of 2.58 x 10^{-4} coulombs per kg (previously defined as 1 esu.cm^{-3} in air of density 0.001293 at STP). This corresponds to the deposition of energy in air at the rate of 87 erg per gram.

The rad and gray (Gy) are units of energy deposition; a rad (100 grays) has been absorbed by the sample of interest when 100 erg per gram (1 joule per kg) has been deposited. One rad thus equals 10^{-2} Gy or 1 centigray (cGy). We can calculate the dose in any material from the exposure in roentgens if we know the relative absorption coefficients for the radiation in air and the material in question.

For 1 MeV photons, the factor for converting roentgens to rads in water is 0.965 rads.$roentgen^{-1}$, i.e. the flux of 1 MeV photons which yields 0.87 rads in air, yields 0.965 rads in water. Some other useful figures on relative photon energy absorption coefficients ((water)/ (material)) are given in Table 19(4).

The figures for glass and Al are very similar at 1 MeV (from which one may reasonably assume that the figures for SiO_2 and Si would be only marginally different, say 1.12 and 1.15 respectively). These figures are useful for calculating relative doses for radiation testing and in-orbit bremsstrahlung. Similar figures can be derived for electrons. The large differences at 100 keV are discussed later.

Even though the gray is the SI unit, the rad is used in this report because this is still the working unit for most published papers on radiation effects and also for current medical practice. Some workers continue to work in "rads", but write "cGy" instead.

TABLE 19(4) - RELATIVE PHOTON ENERGY ABSORPTION COEFFICIENTS ((WATER)/ (MATERIAL)) FOR VARIOUS MATERIALS

	1 MeV	100 keV
H	0.557	0.631
C	1.11	1.19
O	1.11	1.08
Al	1.15	0.663
Fe	1.18	0.117
Cu	1.20	0.0848
Pb	0.82	0.0112
Perspex (PMMA)	1.03	1.08
Polyethylene	0.970	1.05
LiF	1.20	1.14
Glass	1.12	0.788

Measurements of X-rays, gamma rays and electrons with the standard Farmer Dosimeter, which uses air, are performed in a surrounding of material of atomic weight precisely equivalent to water (water-equivalent phantom) under such conditions that the secondary-electron equilibrium setup is that which would be present in water. Doses measured in this way are expressed in rads (H_2O), i.e. rads calculated for water, derived from Farmer air ionisation current measurements. Other secondary dosimeters such as lithium fluoride dosimeters, exposed at the same time, can also be calibrated to read in the same units. In publications on semiconductor radiation effects, the dose scale is commonly given in rad(Si).

19.5.3. Dosimetry used in space simulation testing

19.5.3.1. Farmer air dosimeter

This is a small ionisation chamber dosimeter having thin graphite walls and containing dry air. When placed within a water phantom, it will read effectively the exposure expected in water itself.

19.5.3.2. Thermoluminescent dosimeter

Hot-pressed polycrystalline lithium fluoride chips or powder will absorb a proportion of radiation energy in the form of electrons which remain held in stable traps in the LiF lattice for a very long time at room temperature. On heating to about 150°C, the electron energy is released as light. This thermoluminescence is measured by a cooled photomultiplier and the signal emitted over a given swept temperature range is integrated. The integrated charge from the tube is roughly in linear proportion to the radiation exposure over several decades and thus, with calibration, the value of the charge indicates the dose received. The main advantages of thermoluminescent chips are:

(a) their small size in comparison with the smallest ionisation gauge and
(b) the fact that the dose information can be read later.

Calcium sulphate and $MgSiO_4$ have also been used.

19.5.3.3. Other conventional dosimeters

For doses in the kilorad-megarad range, several other secondary dosimetric media have been used effectively. Photoluminescent silver doped glass and dye-containing plastics have been widely used. Optical colorations in dyed paper, soda glass or alkali halide crystals are also useful for mapping and rough quantitative estimates of dose.

19.5.3.4. Silicon devices as dosimeters

In theory, the effect of radiation on the threshold voltage of a MOS device - given strong oxide fields - should be near-linear over several decades. Early work with discrete MOS transistors demonstrated linearity of ΔV_T versus dose and showed that a 2-wire connection to the MOS device was all that was necessary. More recently, an improved response has been obtained with specially processed MOS devices. A Radiation Measurement Unit designed around these devices by ESTEC staff has been operated on two ESA spacecraft. MOS devices built for dosimetry are called "Space-charge Dosimeters" or "RADFETS" (Holmes-Siedle and Adams, 1986).

Silicon photodiodes are becoming quite commonly used in medical dosimetry and solar cells have been used to measure dose rate.

19.5.3.5. Faraday Cup

For beams of charged particles, a block of metal of the appropriate thickness will stop all the particles and the flow of the resultant charge can, of course, be measured. This arrangement is known as a Faraday Cup and refined forms are used for controlling many electron and proton machines in conjunction with single-particle counters collecting scattered radiation. The main refinements are the evacuation of air around the cup electrode and shaping of the cup so that secondary electrons do not escape.

19.5.3.6. Energy-dependence of dosimetric materials

The problem of dosimetry for encapsulated silicon devices is a particularly complex one, especially when low-energy beams are being used. However, the problems are not insoluble as the energy-absorption physics is well understood and good local dose estimates can be made.

The main problems fall into two fields:

(a) Widely differing photon absorption coefficients for Si, Fe, LiF and H_2O in the otherwise useful low energy region of 30 to 300 keV;
(b) The lack of secondary-electron equilibrium in typical device packages under test.

Owing to the strong dependence of the photoelectric absorption effect upon photon energy and atomic weight (e.g. see Table 10(2) and Johns & Cunningham, 1971), small variations in photon beam energy and the composition of a sample can affect both the attenuation of radiation in the device package and the amount absorbed in the active region. These considerations apply particularly to kilovolt X-ray machines. For X-rays in the 30 to 300 keV range, the dosimeter method used must simulate closely the device packaging and structure while close control must be kept on the penetrating power of the beam.

The energy-dependence problem in LiF dosimetry is adequately explained by reference to the well-known case of "tissue versus bone"; these materials have energy responses not too different from LiF and Si respectively. Energy absorption coefficient changes vary rapidly with photon energy for silicon and bone, and much more slowly for LiF, water and tissue. Thus, a shift of a few percent in photon energy can produce a large disparity in energy absorption between the two groups of materials. This is why control of accelerating voltage is of a high standard in many X-ray sets and must be checked with care in radiation testing. The energy dependence effect is further complicated by an additional dependence of thermoluminescent output per unit dose in LiF, which varies by a factor of 1.27 between 300 and 50 keV.

It will be clear then that potential problems associated with the control and measurement of X-ray dose have received much attention in the field of medical radiology, and methods have been developed to deal with them. The equilibrium question will not be described in detail here. The Bragg-Gray cavity theory concerned is well described in dosimetry manuals. Briefly, at the discontinuity between two dissimilar materials under irradiation, the secondary-electron spectrum and flux characteristic of the first persists for some distance until a new equilibrium ("Compton equilibrium" in the megavolt range) is established. Thus, for example, if a small sample such as a silicon chip is irradiated by Co-60 gamma rays in a steel can (gases being ignored), the silicon receives much of its dose from the Compton electrons generated in the steel.

19.6. TEST PROCEDURES

19.6.1. Introduction

Having described radiation test facilities, we must now discuss how they should be used for irradiating semiconductor devices. The design of a valid space radiation simulation test is not easy. As many ESA contractors may attempt radiation tests, it is important that guidelines for testing be agreed and promulgated, so that these tests are both valid and amenable to comparison. This section does not attempt to present finished guidelines, but discusses recent draft procedures and makes comments on them.

19.6.2. The objectives of procedures

The objectives of a radiation qualification and test procedure are:

(a) To ensure that the long-lived degradation produced by space radiation lies within an acceptable range and
(b) To produce data which will be of further aid to the electronics designer in estimating the degraded "end-of-life" characteristics of the piece part.

It should be noted that these data enable equipment designers to introduce radiation tolerance into their designs in two different ways, namely:

(i) By an "accept/reject" approach, where only the more tolerant devices are accepted for the equipment and
(ii) By a "predict and derate approach", where sensitive devices are accepted and the circuit design allows for quite strongly degraded performance at end-of-life.

The combination of a standard procedure and data processing method should be such that a test procedure and format are achieved which present the information to advantage and enhance design optimisation. An ideal format is the "growth curve" in which the change of a parameter is plotted versus dose (or time in flight at a given spacecraft location). On these curves may be noted the "Fixed Failure Criteria" and the "Stated Dose or Fluence Values" suggested by some authors. The information contained in the full growth curve is more useful than either of the pieces of information mentioned above.

19.6.3. Comparison with military requirements

It will be noted that not all of the above objectives coincide with those of the test for military environments. In the latter, a single total-dose level is often set (e.g. either the "Tactical Environment" with doses in the kilorad range or the "Strategic Environment" with doses in the megarad range). In this case, the doses are in reality received in a few short pulses, so that intermediate points on the growth curve are of no interest. As explained elsewhere, the space designer will be considering components which degrade gradually. Also, of course, the space radiation test can ignore the transient effects of pulsed doses and there is no associated neutron damage. On the other hand, the range of semiconductor components used in the two fields are virtually identical and there is also some overlap with respect to the effects which occur in the two cases. Table 19.5 shows some of the organisations interested in standardising the radiation testing of electronic components. The document numbers of proposed radiation test methods are shown.

19.6.4. SEU procedure

Although two draft documents are known to exist (D. Nichols et al, 1984; E. Petersen and E. Wolicki, 1983), there is no standard SEU testing procedure at the present time. A MIL test method may be expected in the near future. For the correct interpretation of results, the radiation effects community therefore relies, for the time being, on publication of experimental tests. For exposure conditions, the information required is: type of machine, ion species, energy, LET and flux. Details of beam diagnostic techniques should be provided and accuracies quoted.

The techniques employed for monitoring of the device under test are extremely important and should be fully described, software flow charts being used as appropriate. In the testing of complex devices, a number of software and hardware precautions need to be taken, including latchup detection and protection as well as watchdog timers (C. Sansoe and R. Harboe-Sorensen, 1985).

TABLE 19(5) - STANDARDS ORGANISATIONS CONCERNED WITH RADIATION TEST PROCEDURES

Name	Specification number
International	
– ICE	See DIN specifications
– CIFAS	
European	
– SCCG	22900
– EUROSPACE	E-6733
National	
– KMT	KMT 0001/4 and
– DIN	53750 and 53751
– BSI	BS 9000
– CERT	
U.S.	
– ASTM	D 1672, D 2953
– ANSI	–
– MIL	MIL-STD-883, Methods 1018 - 1022
– ANS	–

19.7. RADIATION RESPONSE SPECIFICATION

19.7.1. General

In the many cases where neither time nor funds are available for the radiation hardening of devices, some hardening of a piece of equipment may be achieved by a rigorous selection of commercially available components. Once a specific device type has been chosen, there is still the serious question of assuring that all units in the batches used perform acceptably under radiation. This field, called "Hardness Assurance", has received much attention in military and space work and is a mixture of well-established Product Assurance techniques and special radiation assessment (Wolicki et al, 1985).

19.7.2. Product assurance techniques and special radiation assessment

Institutes in the USA and Europe have developed national and international standards for the assessment of devices under radiation. In Europe, for example, the ESA Space Components Coordination Group (SCCG) has issued a specification. In the U.K., a method for qualifying a series of "Radiation-Assessed Devices", has been circulated by BSI. This was issued by the Ministry of Defence as a draft for the British Standard Institute's BS 9000 series of electronics assessment methods. In the USA, a similar scheme exists under the ASTM and MIL specification systems. Some references to documents are given in the following sections.

19.7.3. ESA/SCC specification (Europe)

The ESA Space Components Coordination Group has developed a draft specification of radiation test procedures (ESA/SCC Basic Specification No. 22900, Draft B, dated 1988). The purpose of this specification is to define the testing of semiconductor devices for the effects of total dose ionising radiation relevant to the space environment. Cobalt-60 gamma rays or electron accelerators may be used.

19.7.4. BS 9000 specification and CECC (Europe)

A draft specification entitled "Specification of Basic Requirements for the Assessment of Semiconductor Components for Tolerance to High- Energy Radiation" has been submitted for a place in the BS 9000 series (BS 900X, Draft J, Sept. 1988). This is a comprehensive specification of radiation test and device assessment procedures, marking methods for BS 9000 device packages, amendments to BS 9000 data sheets and manufacturers' quality assessment. The effects considered include those connected with pulsed radiation, total dose and neutrons. The devices produced to this specification are entitled to the name "Radiation Assessed Devices". Note that this does not imply "radiation-hardened".

19.7.5. MIL specifications (USA)

Radiation standards adopted by the U.S. Department of Defense include the following parts of the MIL-STD System.

- Method 1015 (MIL-STD-750): Steady state primary photocurrent irradiation procedure (electron beam),
- Method 1017 (MIL-STD-883B): Neutron irradiation,
- Method 1019 (MIL-STD-883B): Steady state total dose irradiation procedure,
- Method 1020 (MIL-STD-883B): Radiation-induced latchup test procedure,

- Method 1021 (MIL-STD-883B): Dose rate threshold for upset of digital microcircuits,
- Method 1022 (MIL-STD-883B): MOSFET threshold voltage,
- Method 1023 (MIL-STD-883B): Dose rate response of linear microcircuits.

19.7.6. ASTM specifications (USA)

Radiation Standards adopted by ASTM, a civil body, include the following:

- E 721-85: Standard method for determining neutron energy spectra with neutron-activation foils for radiation-hardness testing of electronics.
- E 820-81: Standard practice for determining absolute absorbed dose rates for electron beams.
- F 448-80: Method for measuring steady-state primary photocurrent.
- F 526-81: Methods for dose measurement for use in linear accelerator pulsed radiation effects tests.
- E 668-78: Standard practice for the application of TLD systems for determining absorbed dose in radiation hardness testing of electronic devices.
- E722-85: Characterising energy fluence aspects in terms of an equivalent mono-energetic fluence for radiation hardness testing of electronics.
- E1249-88: Practice for minimising dosimetry errors in radiation hardness testing of silicon devices using Co-60 sources.
- E763-85: Method for calculation of absorbed dose from neutron irradiation by application of threshold foil data.
- E1250-88: Methods for application of ionsation chambers to assess low energy gamma component of Co-60 irradiators used in radiation hardness testing of silicon electronic devices.
- F1192-90: Standard guide for the measurement of single event phenomena (SEP) induced by heavy ion irradiation of semiconductors.

19.8. DEVICE PARAMETER MEASUREMENTS

This section describes briefly the parameters which are often degraded in silicon devices used in data-handling and also notes some features of their behaviour under irradiation which may require special procedures during testing. Three different desirable sorts of testing are defined: d.c. and a.c. parametric testing and functional testing. The first group discussed here, the d.c. tests, may form a large proportion of those performed for radiation effects.

19.8.1. MOS threshold voltage

The MOS threshold voltage (V_T) has been defined in Section 4. Briefly, it is that voltage at which a certain, practically measurable, channel current (commonly 10 μA) flows after turn-on by inversion. The inversion point in an n-channel device is about 3V more positive than the flatband voltage. Some special problems in V_T ("hysteresis", distortion annealing) are covered by the discussion of C-V plots. V_T may be measured during irradiation, but it must be noted that:

(a) this disturbs the desired stable oxide field condition and

(b) even at a dose rate of 1 $rad.s^{-1}$, photovoltaic effects may interfere.

19.8.2. MOS flatband voltage (V_{FB}) and C-V plot

In an MOS capacitor, threshold channel currents do not exist. However, the whole capacitance-voltage curve contains even more information on the state of the semiconductor and interface. The flatband condition (at which surface potential is zero; hence, no bending of the silicon conduction band) lies on the C-V curve at a point where C/C_O has a value commonly about 0.8, on the depletion side of the minimum of the plot. Unfortunately, the capacitance of an LSI transistor gate is usually so small that most C-V sensing circuits cannot measure it. Special field plates or specially large transistors have to be fabricated; these are not normally provided on commercial integrated circuit chips. Such plates are provided, however, on some Process Validation Modules. Irradiation-induced interface states produce distortions in the C-V curve from which quantitative information can be obtained. One special experimental difficulty caused by irradiation is the production of "hysteresis" in the C-V plot due to the generation of "slow" states.

19.8.3. Quiescent current (I_{SS}) in CMOS logic

The "VTNZ" effect in CMOS logic leads to a drastic increase in current in the power supply circuit. This is usually measured in the V_{SS} circuit or earth leg of the devices concerned, using a nanoammeter. In LSI circuits, where V_T cannot be measured, the measurement of I_{SS} may be the only method available for detecting the onset of the VTNZ effect.

19.8.4. Leakage currents

The reverse leakage of p-n junctions is usually greatly increased by irradiation, especially when the junction is under bias; the field encourages charge build-up on the surface. Current may rise from picoamperes to milliamperes, thus upsetting the impedance matching of the test circuit. These currents will be temperature-sensitive, thus standard temperatures are important. Meters with a wide dynamic range should be used. Dose rates down to 1 $rad.s^{-1}$

can give detectable photocurrents; measurements during irradiation therefore require care.

19.8.5. Current gain

The conventional instrument used for measurement of the current gain of polar transistors is the oscilloscope curve tracer. This displays base current and collector current at several different values and the gain (i.e. the ratio) can be calculated. However, current steps are usually over less than a decade while, as indicated earlier, it is vital to measure radiation-induced degradation of gain over about four decades of collector current.

This illustrates two special features of radiation testing:

(a) Measurements of parameters at values far outside those to be used in flight may provide important diagnostic information on which the expert can base a more confident prediction of degradation in flight.
(b) The routine test instruments may not provide the best form of display or readings for our purpose. For example, the usual set of photographs from the curve tracer is a wholly inappropriate form; much more suitable would be a computer plot of the change in base current I_B versus dose, given for a range of values of I_C or I_E, spread over four orders of magnitude, followed by measurements gained by periodic tracking of the same parameters over several days after irradiation. The complete plotting format as derived by Brown and Horne (1967) is a suitable model to follow.

As explained elsewhere, the surface effect on gain behaves similarly to MOS effects, e.g. it can anneal slowly at room temperature and can often be reduced by heating.

19.8.6. Input offset in analogue ICs

In integrated analogue circuits, only the input and output points are accessible for measurement. The input offset voltage and current are two important parameters in operational amplifiers which degrade very seriously under ionising radiation.

19.8.7. Noise immunity and d.c. switching of logic gates

The switching characteristics of a bipolar or MOS logic gate can be plotted by stepping the input voltage and plotting the output currents or voltages. It is then simple to determine from these curves the loss in noise immunity.

19.9. AC AND FUNCTIONAL TESTING

With large-scale integrated circuits, such as memories and microprocessors, it is essential to test the circuits at the required switching rates and over the full voltage range because, when a number of integrated circuits operate together, the first functional degradation may be the inability of some section to transmit signals rapidly enough.

The same argument, of course, applies to high-frequency communications circuits, where devices may be working near their frequency cut-off or where the tuning of circuits may drift.

19.10. QUALIFICATION OF ENGINEERING MATERIALS

The procedure for testing and qualifying materials other than semiconductors will, in general, be simpler. The demands made on engineering materials are usually less severe, although thermal control and optical materials also require careful testing. ESA has a standard procedure for qualifying materials (J. Dauphin, 1980), but this only requires testing in special cases. Three qualification levels, A, B and C are set, depending on the severity of the intended use of the material. Three forms of sunlight environment are distinguished as shown in columns 1 and 2 (column 3 is our comment) of Table 19(6), and these can apply to qualification level A, B or C. No codes are given for the severity of the ionising radiation environment.

TABLE 19(6) - SUNLIGHT ENVIRONMENT CODES FOR ESA MATERIALS QUALIFICATION

Environment code	Code	Main contribution to damage
R	Outside in sunlight	UV, VUV and kilovolt particles
R	Outside in shadow	Kilovolt particles
R	Inside spacecraft	Mainly megavolt particles and brehmsstrahlung

Of course, packaged electronic devices and their circuit boards will always be "inside the spacecraft".

19.11. CONCLUSIONS

Radiation testing is not a simple art and should be approached by the use of exploratory experiments which will be useful in uncovering any pitfalls. Test design is best assigned to an expert since test facilities are expensive, dosimetry is complex, unusual parasitics are often produced by radiation and statistics may be difficult. Extracting the correct prediction from a small sample of commercial devices requires considerable skill. This section has not attempted to describe a perfect set of facilities or a standard form of test. The problems mentioned prevent rigid standardisation at the moment. The descriptions given are intended to record the current state of the art, with some recommendations and warnings.

It is unfortunate that many of the tests performed never reach publication and are lost to general use. ESTEC is attempting to rectify this by placing some test reports in a data bank, using a standard format for reporting. Additionally, both DFVLR and CNES are building up compendia of test data.

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COMPILATION OF RADIATION TEST DATA

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NASA (USA), Available through P.A. Group, Goddard Space Flight Center, Greenbelt, MD, USA

SPACERAD (USA), Compilation; available through Jet Propulsion Lab., Pasadena, CA, USA and accessible via DARPANET electronic mail system

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