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Donald K. Nichols
William E. Price
Carl Malone

January 1, 1984

Prepared for
U.S. Defense Nuclear Agency
Through an agreement with
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ABSTRACT

A guideline for heavy ion radiation testing for single event upset has been prepared to assist new experimenters in preparing and directing tests. This document describes how to estimate parts vulnerability and select an irradiation facility. It gives a broad brush description of JPL equipment, outlines certain necessary pre-test procedures, and indicates the roles and testing guidelines for on-site test personnel.

The document does not provide detailed descriptions of equipment needed to interface with JPL test crew and equipment, nor does it meet the more generalized and broader requirements of a MIL-STD document. A detailed equipment description is available upon request, and a MIL-STD document is in the early stages of preparation.

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A Guideline for Heavy Ion
Radiation Testing for Single Event Upset (SEU)

1. Introduction

This document has been prepared to provide a guideline for performing radiation tests with heavy ions ($Z \geq 2$) that are used to simulate the effects of primary cosmic rays in outer space on semiconductor devices. Devices which are susceptible to single event upset, manifested as a bit-flip (hard or soft) or as latchup, include the broad category of charge storage devices (RAMs, ROMs, microprocessors, bit-slices, logic devices, etc.) as well as certain devices for which transients may pose a problem (sense amps, NAND gate arrays, PROMs, etc.). The upset is most readily induced as a single bit-flip which can later be rewritten (soft error), but hard errors and latchup have also been observed.

2. Device Appraisal

The first step that any SEU tester should take in estimating the SEU susceptibility of his device is to survey existing data. From this data survey, or from information gleaned from modeling studies, it may be possible to obtain an estimate of the LET (linear energy transfer) threshold for the devices to be tested. Such information can assist in the selection of which ion species (and energy) with which to begin the test runs, using published values for LET for ions of various energies (see, for example, Northcliffe and Schilling). This estimate of the LET threshold will be an important factor in the selection of the proper facility. At the present time, much of this data has not been published in the open literature, so personal communication with the leading SEU experimenters whose names are given in recent publications of IEEE Transactions of Nuclear Science (December) is a useful first step. JPL has published their data taken through May 31, 1982 in a report available upon request (D.K. Nichols, "Single Event Upset (SEU) of Semiconductor Devices - A Summary of JPL Test Data"). Aerospace has also performed numerous heavy ion tests¹.

To estimate the LET threshold for a given device one can use the following approach. Firstly, one should look for data for devices having a similar function and technology with similar feature sizes (transistor density), irrespective of the manufacturer. If alpha particle data is available, any observed upsets would indicate a very sensitive device* of

* Note that some manufacturers test their devices with an alpha particle source to determine whether radioactive contaminants in the package are capable of causing upset. If they see upsets and solve the problem by introducing filler material to stop radioactive alphas, they do not succeed in preventing upsets from much more energetic cosmic ray alpha particles.

threshold LET ≤ 1 MeV/mg/cm². If proton data is available, any upsets also show a sensitive device, probably with an LET threshold ≤ 6 MeV/mg/cm². If heavy ion data is available, then that data provides a very crude estimate of what might be expected for the device to be tested. If no data is available, one should assume that certain technologies and function have a high risk for upset. For silicon devices, a rough division is given below.

HIGH RISK DEVICES:

- 1) Bipolar RAMs (fast speed)
- 2) Low power logic
- 3) LS (low power Schottky) logic
- 4) Microprocessors and bit-slices
- 5) NMOS, PMOS
- 6) Dynamic NMOS RAMs

LOWER RISK DEVICES:

- 1) Some CMOS bulk devices
- 2) Some CMOS/SOS technology
- 3) Some standard power logic
- 4) PROMs
- 5) Slow speed devices
- 6) Large feature sizes (≥ 10 microns)

3. Facility Selection

There are four broad categories of ion sources that have been used successfully for single event upset studies. Which category is most suitable depends on the money available, the fundamental system requirements and the device appraisal (see Section 2).

3.1 Fission Sources

The use of a fissionable material, such as Californium-252, is presently in the developmental stage. Researchers have shown that the spectrum of fission products have an LET of 45 to 50 MeV/mg/cm² which is far more likely to induce SEU than the heaviest ions in space (the iron group with a maximum LET of ~ 30 MeV/mg/cm²).

This source may ultimately find an application for inexpensively screening out those parts which are very resistant to SEU. However, those parts which exhibit upset in this source may still have a useful system application and will have to be tested by another source in order to be fully characterized in terms of their LET threshold and upset cross section.

3.2 Alpha Emitters

Naturally occurring radioactive alpha emitters provide another source for screening out parts that are very sensitive to SEU. In many cases, those parts susceptible to alpha particle upset will not be suitable for a proposed space or satellite system. Because alpha emitters emit particles with a spectrum of energies (1-15 MeV), they are not useful for establishing a threshold LET. Hence a full SEU characterization of the LET threshold and the cross section at higher LET will require another source.

3.3 Cyclotrons

Cyclotrons provide the greatest flexibility of test options, since they can supply a number of ions (including alpha particles) at a number of different energies. The maximum available energy of the heavy ion machines is always greater than that corresponding to the maximum LET (energy ≈ 2 MeV/nucleon) and the ions have adequate penetration (range) in the device. The disadvantages of cyclotrons are their expense and the long down-times associated with ion source replacement, changes of ion energy and change of the ion species.

A complete compilation of available cyclotrons is given in Reference 2. A first consideration should be given to the following list of machines because of successful past experiments, or because of demonstrated interest on the part of the facility.

- 1) UC Berkeley 88" cyclotron (Lawrence Berkeley Labs)
- 2) Oak Ridge cyclotron (Heavy Ion Laboratory)
- 3) ALICE cyclotron (Institute Physique Nucleaire, Orsay, France)

Any particle accelerator must be capable of providing a uniform beam (fluctuations $< 10\%$ across two orthogonal axes) with a beam radius of adequate size (radius > 1 inch). The beam must have the required intensity (typically 10^3 to 10^5 ions/cm²-sec.) which is usually much lower than the customary intensities used at large facilities. The beam must pass through an evacuated tube with adequate instrumentation (magnets and monitors) for steering and defocusing to assure uniformity and proper intensities. Real time flux measurement capability is a desirable feature of any facility, but often does not exist for the low intensity beams used in SEU experiments. In general a large variety of ion species and energy levels for each ion species is a desirable capability for any facility. Beam energy degradation by insertion of foils is possible in those cases where a broadening in the energy (and the range) of the degraded beam does not cause a problem in data interpretation and where the presence of some reaction by-products is acceptable.

All cyclotrons deliver beams in a series of pulses which vary tremendously among machines. In some cases the instantaneous flux (particles/cm² per second) may be very large during the short duration of each pulse. Care

must be taken to assure that this flux (localized in time) is not so high that it can introduce upset from the charge deposited locally by several ions arriving in a given pulse, in a manner similar to that induced by short transient flash X-ray or LINAC bursts. In some cases, the pulse conditions of the machine can be adjusted to assure that the transient burst phenomenon does not take place.

3.4 Van de Graaff Accelerators

Van de Graaff accelerators provide another important ion source. However, because the energy is limited*, care has to be exercised to make sure the ion range is adequate. This source is especially useful for pinpointing LET thresholds of sensitive devices corresponding to lower Z ions where rapid energy variation and/or rapid change of ion species is desirable. Costs for Van de Graaff rental are also substantially less than for the UC Berkeley 88-inch cyclotron.

Candidate Van de Graaff machines are available at Caltech, U. of Pennsylvania, U. of Washington, Oak Ridge, Brookhaven National Laboratory and elsewhere.

4. Basic Equipment

A heavy ion test requires certain basic equipment to be provided by the experimenter, consisting of:

- 1) Vacuum chamber
- 2) Beam energy measurement system
- 3) Flux measurement system
- 4) Beam uniformity measurement system
- 5) Test cards and positioning system
- 6) Device tester (exerciser)

4.1 Vacuum Chamber

A suitable vacuum chamber, such as that used by JPL, is described here. (See Figure 1.) The vacuum chamber, housing the DUT, test card, and the beam diagnostic equipment, connects to the evacuated accelerator beam line. It should contain a vacuum of 10^{-5} Torr or less to avoid introducing excess gases into the accelerator. A well-designed vacuum chamber should have an access port for easy removal and replacement of the DUT test card, valving to permit fast pump-down, visibility of the test card, and should also be built in such a way that internal pressure changes do not rupture the sensitive scintillator foil. The vacuum chamber also must contain equipment for positioning and rotating the DUT within the beam.

* One exception is the new Oak Ridge machine which can deliver an energy > 2 MeV/nucleon for many ions for atomic numbers up to that of gold.

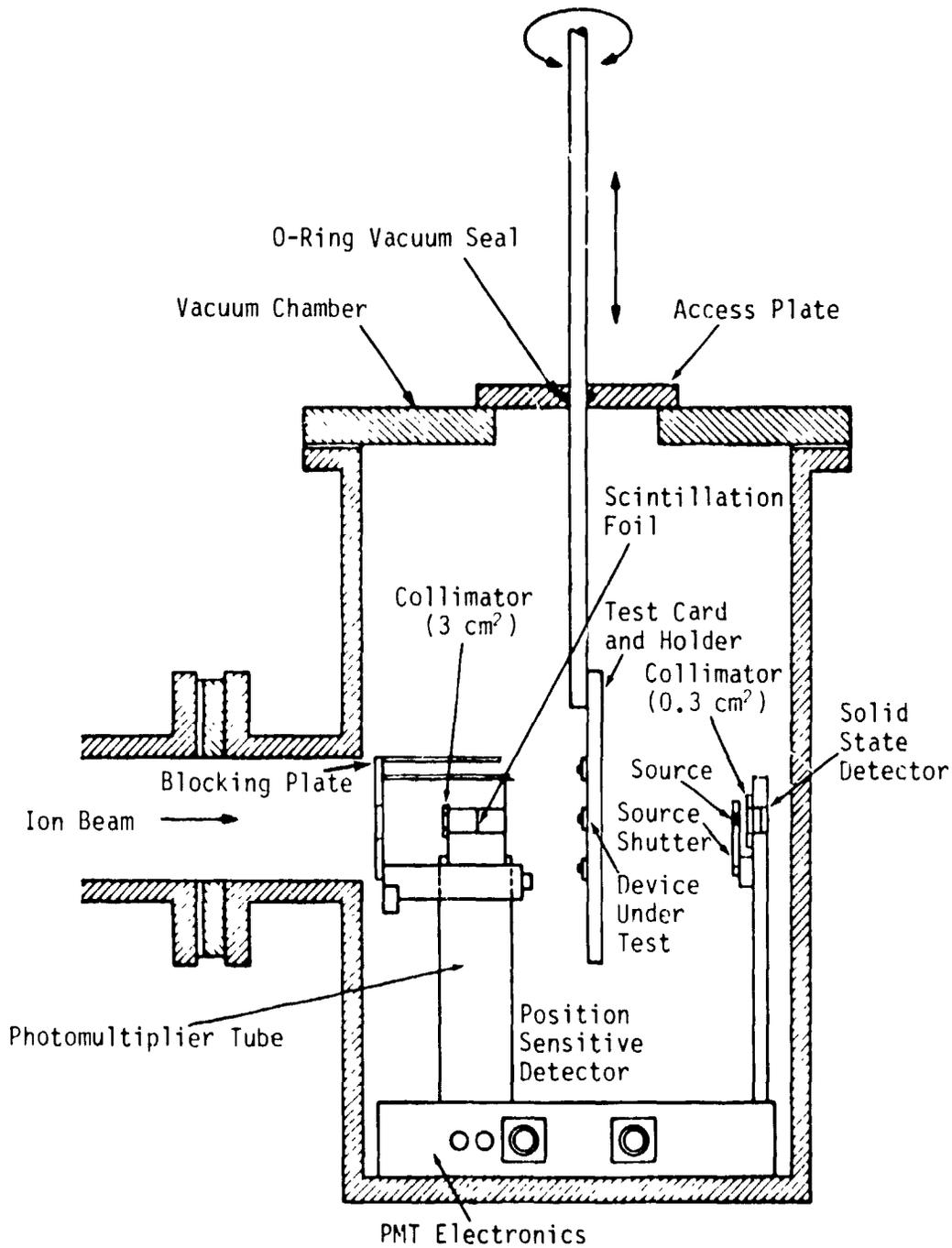


Figure 1. JPL Vacuum Chamber

4.2 Energy Measurement System

The energy measurement system must have adequate energy resolution to determine the beam energy and (in some cases) the proper selection of the elemental ion, and provide a check on the energy spectrum to assure that no scattered beam is present. The energy resolution is limited by the accuracy of the multichannel analyzer (MCA) calibration and the extrapolation from a reference ion source to the higher energy of the accelerator beam ions. In general, the LET variation with beam energy is rather small, so strict requirements on the energy (or energy spread) may not be warranted.

This system (see Figure 2) consists of a bias supply, test pulser, surface barrier detector with collimator, preamplifier, spectroscopy amplifier, multichannel analyzer, and calibration source.

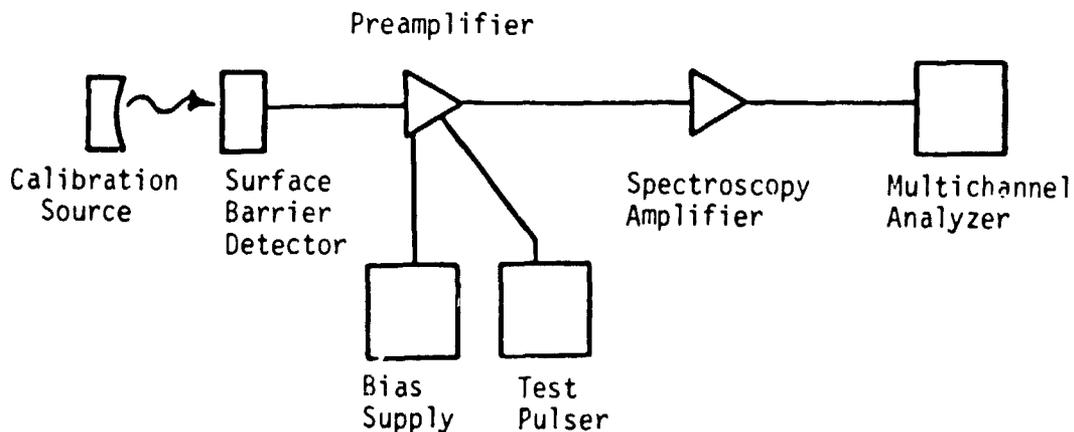


Figure 2. Energy Measurement System

4.3 Flux Measurement System

The JPL system consists of a scintillation foil, light pipe, photomultiplier tube, phototube base, collimator, high voltage power supply, discriminator, counter, and rate meter. (See Figure 3.)

One virtue of this approach is that it gives a real time readout of the flux and fluence falling on the DUT. The flux measurement system has the ability to count the ions per square centimeter per second in the beam while introducing a minimal energy loss ($<20\%$) to the beam. This system also has the ability to count ions of varying energies with the necessary accuracy to fit the experimental requirements.

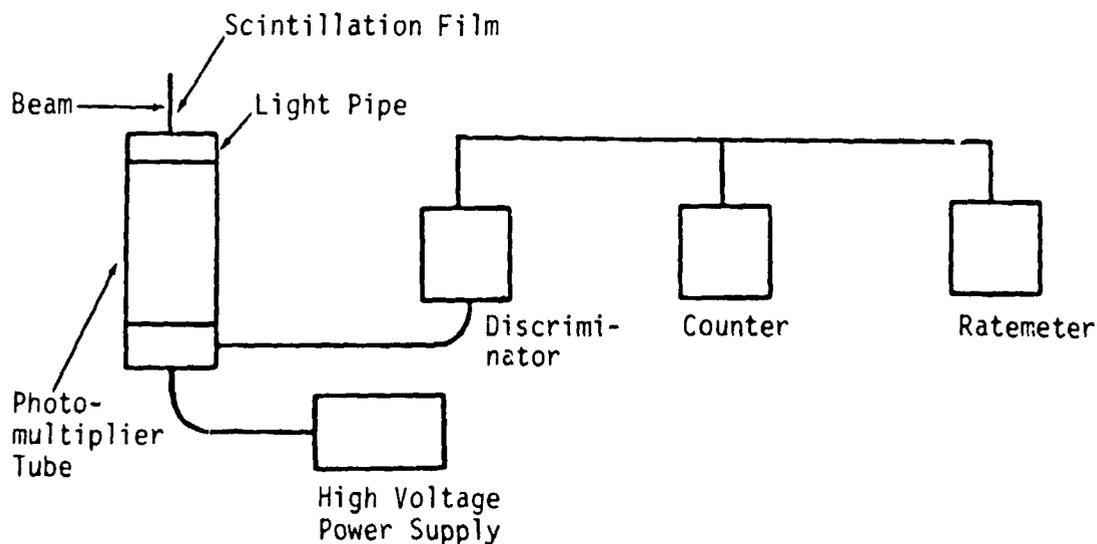


Figure 3. Flux Measurement System

4.4 Beam Uniformity Measurement System

The beam uniformity measurement system must provide an accurate (within 10%) determination of the uniformity of the collimated beam sent to the DUT. The JPL system consists of a position sensitive surface barrier detector, which when placed behind a narrow slit can provide a display of that slice of the beam on a multichannel analyzer (MCA). The detector is positioned above the test card in the vacuum chamber and can be moved up and down in the beam. Included with this equipment are two preamplifiers, two pulse shaper amplifiers, a position resolver module, a test pulser, a MCA and the slit collimator.

4.5 Test Card and Positioner

Because the vacuum chamber is typically situated in a cave, or radiation-shielded and darkened room (because of light sensitive detectors in the chamber), it is very desirable to have a remote, automated system for moving the test card vertically, or at an angle, with respect to the beam. Vertical motion permits removal of the card from the beam without breaking vacuum, or device selection when two or more test devices are vertically positioned on a single card. Angular positioning of the card with respect to the beam is important to any heavy ion test because it results in a longer effective beam path in a sensitive volume. Angular data can also be used to determine whether the device is near the LET threshold (large increase in upsets at larger angles) or whether the beam has a limited range with respect to device depth dimensions (large decrease in upsets at larger angles). The positioner is an electromechanical device, consisting of stepper motors and indexers to provide the motion, coupled through gearboxes and lead-screw assemblies. Counters are added to the indexers to give a direct reading of height and angle. The JPL system can be run entirely from the experimenter's location, and also permits the uniformity detector to be swept through the beam.

The test card is simply a PC board of the proper dimensions to be affixed to the metal test frame, which has a cylindrical rod extending beyond the vacuum chamber lid through a vacuum seal. The card has fixtures (sockets) for the device under test (DUT) as well as the necessary electronics (logic devices and transceivers) necessary to exercise the DUT and to transmit data to and from the chamber. Because the test card operates in a vacuum, any material that outgasses (epoxy resins, tape, potting compounds, grease, etc.) should not be used on it. Also, any electronic component that might overheat must be provided with a heat sink because the vacuum prevents any convective heat dissipation.

4.6 Device Tester (Exerciser)

Many different types of device testers can be developed to test individual families of devices, and it may be proper to design such a tester for the single device type to be tested. However, if testing is planned for a large assortment of different device types or if future testing is foreseen, it may be desirable to design and build a "universal" test system that can be applied to all such devices.

5. Pre-Test Procedures

Pre-test procedures described below include parts preparation, tester checkout, dosimetry check-out, installation and alignment of equipment, provision for latching monitoring capability, and particle beam preparation. Installation of shielding blocks may be required to prevent total dose accumulations on certain sensitive components in the equipment (e.g. tester).

5.1 Parts Preparation

All parts must be delidded to permit passage of the heavy ion beam to the chip face. Because delidding may result in up to 50% loss of parts, these devices must be subjected to a follow-on functional test. Care must be taken to order the proper package type for use in the test card, but ceramic packages should be avoided because of the difficulty in delidding them. Flatpacks will need flatpack holders with a hole in the lid to permit direct exposure of the chip to the beam.

5.2 Tester Check-out

A device tester "dry-run" with the DUT in place should be performed prior to the test. It is strongly recommended that this check-out be performed with all equipment that will actually be used on-site, including the long cables that are required to connect the DUT outside of the irradiation area (cave).

5.3 Dosimetry Check-out

Close coordination between the user and facility is required to assure proper real time flux measurements. For the low fluxes used in SEU experiments, it is highly probable that special dosimetry will be required. In some cases, with proper lead time, it may be possible for the facility to develop dosimetry in the desired flux range, but usually a special system such as described in Section 4.3 will be required.

For this scintillating foil/photomultiplier assembly, it is necessary to provide foils of appropriate thickness for the LET of beams that will be used. The bias must be applied to the photomultiplier tube (PMT) gradually until the pulses are of adequate size to permit discriminator adjustment. The discriminator must reject all noise pulses and pass all pulses caused by

the beam. The beam intensity must be kept below the point that causes photomultiplier tube saturation.

5.4 Installation and Alignment of Equipment

The vacuum chamber must be connected with the evacuated beam pipe of the accelerator through a roughing pump. Opening and closing the vacuum chamber is quite wasteful of time, so purchase of a user's roughing pump may be worthwhile. Alignment of the equipment can be accomplished visually; however, a laser source provides a faster and more accurate method.

5.5 Latchup Monitoring Capability

To monitor latchup, a current-limited power supply should be used with on/off switch and ammeter located in the monitor room. If a resistor is used in the supply line to limit the device current, it should be small enough to permit an adequate latchup sustaining current to be delivered to the device, since a high resistance can circumvent latchup. Once latchup has taken place, it is necessary to shut off power to the chip quickly in order to prevent device burn-out. If this has been accomplished automatically, the power shut-down should be flagged so that the experimenter can simultaneously record the heavy ion fluence. A limited number of repeat measurements can be taken on a latchable device after a waiting period to allow the device to cool down.

In more sophisticated tests it may also be desirable to 1) guarantee that the device is not destroyed, 2) determine the time before burn-out for specified current conditions, 3) determine the maximum latchup current, 4) determine the maximum latchup current that will not cause burn-out, etc. Such tests may require microscopic examination or analytic study of the device and will assuredly require a detailed test plan to answer the specific system requirements.

5.6 Particle Beam Preparation

Particle beam preparation can be a long (one to twelve hours) and arduous process requiring close interaction between the facility operator and the user. The ion species delivered by a Van de Graaff accelerator or a cyclotron can never be taken for granted, especially for higher Z ions, so the first priority of the user is to verify the ion species. At the same time the user will need information on the ion energy (or its spectrum), the available range of fluxes, and data on beam uniformity to permit the facility operator to make necessary beam adjustments (e.g. focusing, magnet steering, etc.).

The energy measurement system must be calibrated using a radioactive source (e.g. Th-228). After the beam flux has been lowered sufficiently to avoid pileup in the detector(s), an energy spectrum is accumulated and

displayed on a multichannel analyzer (MCA). The accelerator operator states what beam energy he thinks the machine is producing and this is compared with the display on the MCA. If the beam passes through any foils the resulting energy loss and spread must be taken into account.

The shape of the MCA display indicates if any scattered beam is present and the location of the peak indicates whether or not the desired ion species is present. Any undesired species present is usually due to mistuning or instability in the accelerator or bending magnets.

After the proper ion species and energy have been obtained, the uniformity of the beam must be measured and adjusted for a beam spot of ≥ 1 inch diameter. At JPL, uniformity measurements are taken using a position sensitive detector and displayed on a multichannel analyzer; then adjustments are made using beam focusing techniques or thin scattering foils to diffuse the beam.

In general, changes of the following beam conditions can be made according to the ranking given below where 1 is the easiest:

- 1) Change flux (within certain limits)
- 2) Correct beam uniformity
- 3) Change beam energy (specified discrete energy increments in a cyclotron; continuous in a Van de Graaff)
- 4) Change to a new ion species (complete retuning in a cyclotron; may be trivial for a Van de Graaff)

6. Testing

A test plan, prepared before testing, will serve as a guide for the procedures and decisions to be made on-the-run during the actual irradiation period. However, no test plan can be followed slavishly, because there are too many accelerator variables and the results of previous data runs to be factored into later runs.

In planning, one should allow up to eight hours for the facility operator to bring the cyclotron to the point where it delivers the correct ion, at the correct energy at the designated flux and with a suitable uniformity. One or two hours should be allowed for every change in beam energy at the cyclotron and two to four hours for a change to a new ion species. Changes in flux requirements will probably occur, and two hours should be allowed for this for every eight hour straight run. A sustained run with one ion species will use up the source every three to six hours (depending on ion species) and will require one or two hours to replace. Contingency time should also be allowed for beam diagnostics, unforeseeable cyclotron downtime and tester malfunction. Two or three hours per eight hour run is a realistic (not a conservative) estimate for these latter factors.

Large facilities usually prefer a straight uninterrupted time slot, say twenty-four or seventy-two hours. Hence a test team should consist of at

least four men who can spell one another and perform more than one function. The number of active testers should be no fewer than three at any given time. Their functions are:

- 1) Test Director: The director has absolute authority over all aspects of the test, interfaces with the facility personnel, and supervises all others present at the test site; he has responsibility for personnel safety, protecting the accelerator vacuum, assuring proper interface preparations with the machine, and allocating time for the test segments. He takes the data, digests its implications and prescribes conditions for the next run. The director will also be responsible for writing the test report.
- 2) Beam Dosimetry Engineer: The beam dosimetry engineer has the responsibility for seeing that the beam meets test specifications. He interfaces closely with the machine operator to obtain the beam, works to achieve satisfactory beam uniformity, and prepares and fully understands the dosimetry equipment and beam problems. During runs the engineer controls the fluence by activating the shutter, and is also responsible for recommending beam diagnostics and keeping track of the status of the accelerator source.
- 3) Tester: The tester is responsible for running the tester, diagnosing its problems, pre-test functional check-out of the parts, parts control, and installation of parts in the vacuum chamber. The tester should have "hands-on" electronics experience in order to correct board, cabling and electronics problems that invariably arise. He will be responsible for collection and preshipment of all necessary test equipment including tools, spare parts, schematics, operating manuals and electronics equipment.

During the test, it is imperative that the director fully understand the implications of the data; including the LET and range of all particles at the beam energy being used, or available for use, and have some familiarity with the device process and mode of operation.

If the device does not upset there are several options available to the director:

- 1) Increase flux (10^8 ions/cm² is an adequate integrated flux)
- 2) Change beam angle. Flips with the beam at oblique angles indicates that the device is near threshold.
- 3) Change to another part of the same device type.
- 4) Change operating parameters, including initial load configuration
- 5) Go to another device type
- 6) Change ion energy
- 7) Change ion species

If the device upsets, there are also several options available:

- 1) Change flux to get a statistically meaningful number of upsets without overloading device tester or dosimetry
- 2) Change beam angle
- 3) Change operating parameters, including initial load configuration
- 4) Repeat runs to give a statistical measure, or to verify beam stability
- 5) Go to another part of the same device type to measure part-to-part variability
- 6) Go to another device type
- 7) Change energy of ion to give a new LET. A lower LET would permit convergence on the LET threshold. (Note that a lower energy does not imply a lower LET.)
- 8) Change ion species to introduce a new range of LET values for the beam.

7. Test Documentation

7.1 Final Report

The test documentation shall consist of a final report which will include:

- 1) Introduction giving background and rationale (objectives) of the test.
- 2) Complete parts description, including number of flip-flops per device.
- 3) Description of experimental set-up and methods. The description should also include accelerator beam characteristics and relevant details of the parts tester (exerciser).
- 4) Presentation of data. (See Section 7.2.)
- 5) Descriptive interpretation of data (e.g. LET threshold, cross sections).
- 6) Test problems and recommendations as part of a concluding overview.

7.2 Data Sheet

The data sheet to be included as a part of the final report should include the following:

- 1) Dates, times, names of test director and crew
- 2) Beam type and energy
- 3) Part type, serial number, functional description and manufacturer
- 4) Reason for each test run; give changes from previous test run
- 5) Device operating parameters (bias, frequency, temperatures, etc.)
- 6) Device test pattern or operational mode
- 7) Beam angle

- 
- 8) Beam counts (related to fluence), run time
 - 9) Number of errors and special comments. The address location of the errors need not be reported here, but a record should be kept elsewhere to permit analysis for preferred flip-direction, randomness, possibility of adjacent upsets, etc.
 - 10) Blocks of data relevant to a particular test goal should be indicated by underlining to facilitate reader interpretation of data and trends.

References

- 1) Contact Dr. Al Kolasinsky or Dr. J.B. Blake, Space and Sciences Laboratory, The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009.
- 2) John A. Martin, "Cyclotrons - 1978", IEEE Transactions on Nuclear Sciences, NS-26, No. 2, p. 2443, April 1979.