DESIGN CONSIDERATIONS AND TEST FACILITIES FOR ACCELERATED RADIATION EFFECTS TESTING*

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Test design parameters for accelerated dose rate radiation effects tests for spacecraft parts and subsystems used in long term missions (years) are detailed. A facility for use in long term accelerated and unaccelerated testing is described.

INTRODUCTION

Outer planet missions require electronics and science instruments that have a useful lifetime of up to ten years. During this time, they are continuously within the gamma and neutron fields of the radioisotope thermoelectric generator (RTG), which provides electrical power to the spacecraft. Additionally, these electronics and science instruments are subjected to a number of other radiation stresses: Jovian radiation belts, solar flares, solar wind and cosmic radiation. One means of verifying the adequacy of components and of design for the ten-year useful lifetime is by accelerated testing in an adequately simulated environment. The intent is to simulate, in a short testing period, the effects to be expected in the real spacecraft mission, taking into account all of the stresses involved in radiation-cryogenic-vacuum environments.

RADIATION SOURCE CONSIDERATIONS

Jovian Radiation Belts

The Jovian radiation belt simulation testing need not be accelerated. This is because the belts may be traversed in a few hours on flyby missions. Both electrons and protons are expected to be trapped in the Jovian magnetic field, although the only direct estimates that have been made imply only an electron flux. It appears that readily available particle accelerators can simulate the Jovian fluxes in real time for both electrons and the theoretical models for protons.

Solar Flares

Solar flare rates will be lower than the Jovian radiation belts and the total doses can almost certainly be obtained by allowing 0.5 h/flare (acceleration by a factor of about 100). A twelve-hour test will conservatively simulate a ten-year mission.

Cosmic Radiation

The flux of cosmic ray particles is small and the expected damage is too low to be considered as an important area for environmental testing.

Solar Wind

The solar wind, whose effects are manifested as surface problems, has not interfered with past missions. The average flux of solar wind particles over a twelve-year period, with an assumed average energy of 3 keV, is 10^7 protons/cm^2-s. Although at 1 AU the flux is 10^8 protons/cm^2-s, the $1/r^2$ decrease means that at Jovian distances, the flux is reduced by a factor of 1/25. Since 3 keV protons have a range of 10^{-5} g/cm^2, if we assume a target with a thickness equal to the proton range, the delivered power density is 4.8×10^{-8} W/cm^2 at Jupiter orbit. For those components that rely on radiative cooling for their heat loss, typically unsupported thin films, too great an acceleration of the above given natural solar wind rates may lead to annealing effects in the test, which are not present in the real space environment.

The power radiated from a black body (in watts/cm^2) is equal to $(T/645)^4$ where T is the temperature in degrees Kelvin. Table 1 gives the expected equilibrium temperature of a radiatively cooled thin film, subjected to various accelerated dose rates of solar wind, calculated for various initial component temperature and power densities. In programming a test, larger accelerations (that lead to larger temperature rises) can be tolerated for systems that operate at low temperatures than for systems that operate at high temperatures, because the annealing temperature is related to the Debye temperature for the material under test. These restrictions are further relaxed when more efficient means of cooling may be employed (e.g., conductive cooling to the spacecraft for non-thin-film components).

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Table 1. Equilibrium temperature of a radiatively cooled thin film, subjected to various doses of (accelerated rate) solar wind

Acceleration, times nominal	Duration of test	Power density, W/cm^2	Initial component temperature, °K	Equilibrium temperature, °K
Earth orbit				
1	3650 days	4.8×10^{-8}	300 (earth assumed)	300
10^2	36.5 days	4.8×10^{-6}	300 (earth assumed)	300
10^4	0.36 day	4.8×10^{-4}	300 (earth assumed)	300.5
10^5	5.2 min	4.8×10^{-3}	300 (earth assumed)	308
10^6	0.52 min	4.8×10^{-2}	300 (earth assumed)	358
Mission average				
1	3650 days	4.8×10^{-9}	300 (assumed)	300
10^2	36.5 days	4.8×10^{-7}	300 (assumed)	300
10^4	0.36 day	4.8×10^{-5}	300 (assumed)	300.1
10^5	5.2 min	4.8×10^{-4}	300 (assumed)	300.5
10^6	0.52 min	4.8×10^{-3}	300 (assumed)	308
Mission average				
1	3650 days	4.8×10^{-9}	150 (assumed)	150
10^2	36.5 days	4.8×10^{-7}	150 (assumed)	150
10^4	0.36 day	4.8×10^{-5}	150 (assumed)	150.6
10^5	5.2 min	4.8×10^{-4}	150 (assumed)	155
10^6	0.52 min	4.8×10^{-3}	150 (assumed)	192
Jupiter orbit				
1	3650 days	1.78×10^{-9}	150 (assumed)	150
10^2	36.5 days	1.78×10^{-7}	150 (assumed)	150
10^4	0.36 day	1.78×10^{-5}	150 (assumed)	150.1
10^5	5.2 min	1.78×10^{-4}	150 (assumed)	152
10^6	0.52 min	1.78×10^{-3}	150 (assumed)	169

RTG Radiation

Gamma Radiation

The spectral distribution and intensity of the gamma field from the RTG, although varying with time and dependent upon the initial fuel composition and construction of the RTG capsule, have been extensively studied at JPL.

The design considerations given in this paper indicate the practical limits of acceleration of testing, and take into account costs, radiation safety needs and requirements for spatial uniformity of accelerated test fields.

The analysis is based on a generalized outer planet spacecraft configuration in which the RTG-science-instrument spacing is taken as 180 in., and the RTG electronics spacing is taken as 72 in. Actual design geometry and environmental conditions will be determined as the program proceeds. The analysis is based on the simulation of the radiation of an 8000 W (thermal) source, as was envisioned for an earlier JPL TOPS configuration. Newer configurations may have somewhat different radiation levels, but such changes will not change the conclusions of the study.

Acceleration of delivery of total dose is accomplished by increasing the dose rates delivered to the test object by either of the two methods described below, or by the use of both simultaneously.

Loading

Increasing the gamma flux by using larger amounts of nuclear material or a satisfactory nuclear species that gives the same gamma spectrum. The apparent limitations are in cost and safety necessary for large sources. A practical acceleration of X 25 (over the output of an 8000 W (thermal source) can be had for a moderate cost. The X 25 acceleration source could be used in the JPL 25-ft space simulator (see Fig. 1).

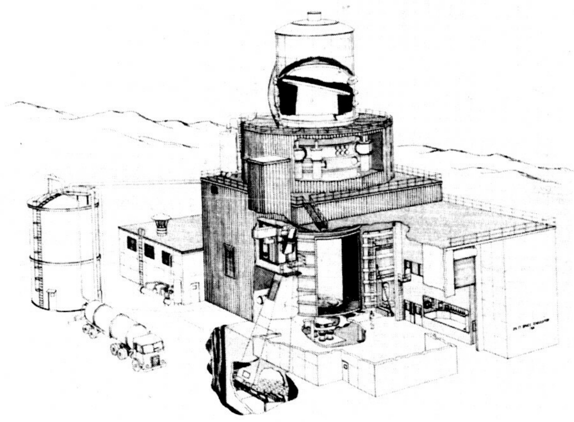


Fig. 1. JPL 25-Ft Space Simulator

An alternate loading acceleration has been designed that would use a fast decaying, but intense source of sodium-24 as the principal nuclide. This design allows a loading acceleration of X 250 at slightly more than twice the cost of the X 25 source. However, this source could not be ready for use in less than approximately eight months.

Geometrical

An increase in the gamma flux can be had by bringing the source closer to the test objects than the design value of 15 feet for the science instruments, and six feet for the electronics. When the source real or simulated, is placed closer than its normal separation distance from the test object, the field strength is increased by the ratio $15^2/d^2$ or $6^2/d^2$ for science instruments or electronics, respectively. The uniformity of the exposure from the near-face to the far-face of the test object, however, decreases as the distance d from the source to the test object decreases. Practical geometry increases are from X 10 to X 100, depending on the size of the test object and the uniformity of flux required.

Because of the deep penetration of the gammas, the heat input per unit volume of the test object is low, and annealing is not expected to be a problem, even for a X 2500 acceleration.

Figure 2 shows the uniformity of dose (in terms of tolerance from the centerline dose) for varying distances up to 200" from the source and for test objects whose size (extent in the beam direction), is 2, 4, 8, or 16 in. The figure shows that a geometrical acceleration of X 10 may be had for a 4-inch-thick object with a uniformity of $\pm$ 6% of centerline intensity, while a geometric acceleration of X 100 yields a variation of $\pm$ 20%. Similarly, Fig. 3 shows the uniformity of dose (from centerline dose) and geometrical acceleration possibilities for electronic bay equipment, which is normally six feet from the source.

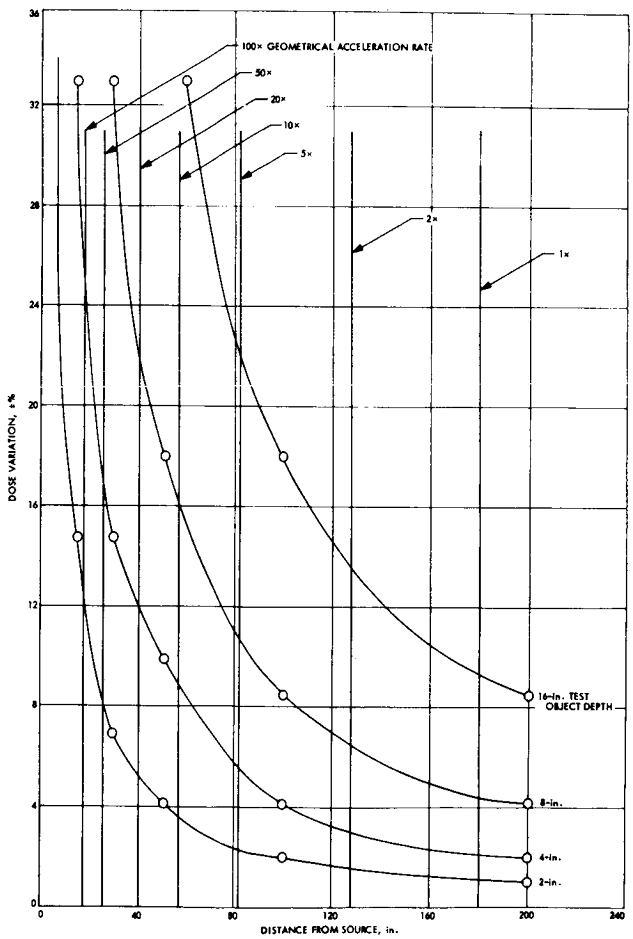


Fig. 2. Uniformity of dose as a function of distance from the source for various test objects

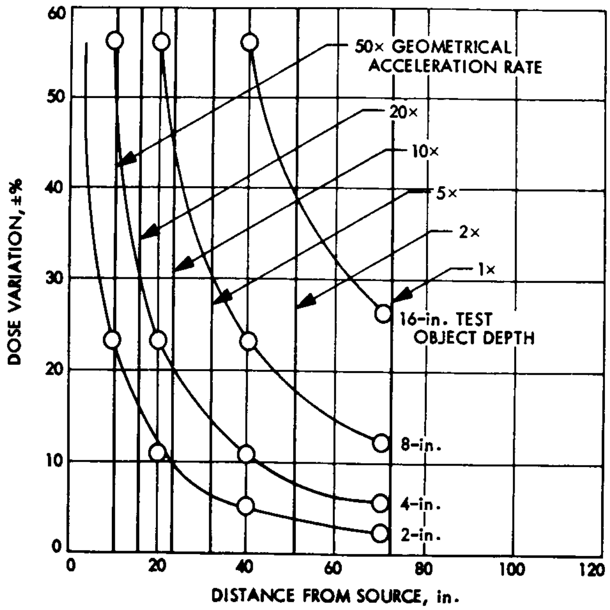


Fig. 3. Uniformity of dose as a function of distance from the source for electronic bay equipment

Neutron Radiation

It does not seem practical, at present, to make large loading accelerations for the neutron flux components of the RTG radiation. Therefore, any acceleration using isotopic sources will be dependent on increases via geometrical means. Studies are underway to determine if larger geometrical accelerations can be tolerated for neutrons than for gammas, because of the different nature of the scattering and interaction mechanisms involved.

An alternate possibility exists for accelerated neutron testing in the use of a machine accelerator as a neutron source. While this has some limitations on size of component accepted, the energy spectrum can be grossly simulated and fluxes as high as 10^{11} n/cm^2-s can be attained in small areas at JPL.

COMBINED ENVIRONMENTS AND TESTING CONDITIONS

Simultaneous application of other space environments (space vacuum, solar and ultraviolet irradiation, and control temperatures down to those of liquid nitrogen) will also be possible in the JPL facilities.

Table 2 shows a selected set of operating conditions that are available using a combination of loading and geometrical accelerations. In each case, it is possible to increase the irradiation uniformity (decrease the variation) from that presented in Figures 2 and 3 and in Table 2, to a small fraction of the given values by mounting the test objects on a rotating table, or a table that oscillates through 180 degrees, so that the two faces of test objects alternate in their exposure to the source.

Table 2. Operating conditions for accelerated testing (10-yr mission length)

Acceleration, times nominal			Required total test duration, days	Remarks
Loading	Geometrical	Total		
10	10	100	36	±12% uniformity for 8-in.-thick test object
25	10	250	14	±12% uniformity for 8-in.-thick test object
10	100	1000	3.6	±10% uniformity for 2-in.-thick test object
25	100	2500	1.5	±10% uniformity for 2-in.-thick test object
250	10	2500	1.5	
250	30	7500	0.5	

ACCELERATED RADIATION EFFECTS TESTING FACILITIES

Comparatively little work has been done to determine if long-term (years), of low level radiation environments such as encountered by spacecraft on long missions, will affect the lifetime and reliability of spacecraft parts. Most of the existing radiation effects studies have concentrated on material property studies, weapons effects, and reactor irradiations which are of little value to radiation effect studies for outer planet missions. Space radiation simulation has been done on a limited number of device types used in present day spacecraft (Ref. 1).

Accelerated testing is important to obtain data in a practical time. To be useful, however, a relationship must be established between parts testing in real time using combined environments (under varied test conditions) and accelerated testing to take the rate effects, if any, into account. Such a program of studies is indispensable for carrying out present outer planet missions. An initial simple program is described below. As the requirements become clear, additional variables may be added at the expense of increased complexity and cost.

The major object of the program described is to determine for a large number of types of parts, whether accelerated testing is a valid procedure to predict long-life, real time operation in a low level radiation field, and if so, to define for various parts and components what rate of acceleration can be tolerated in testing. Standard testing procedures must be developed and validated for the parts to be tested.

An Accelerated Radiation Effects Laboratory has been put into operation at JPL in a group of former explosive test cells. A source of radiation, 5 curies of Ir^{192}, was placed in a collimator with the radiation beam directed toward the ceiling (see Fig. 4). Circuit boards of parts and components are suspended in the cone of radiation at two or three distances from the source to obtain different radiation dose rates. Some of the parts will be non-operating and some will be operating to simulate conditions on a spacecraft (where some systems are continually in operation while others are used intermittently or only at planet encounters). There will be control specimens subject to the same environmental conditions except for the radiation, and these will be operated by the same power supplies as those powering the irradiated samples.

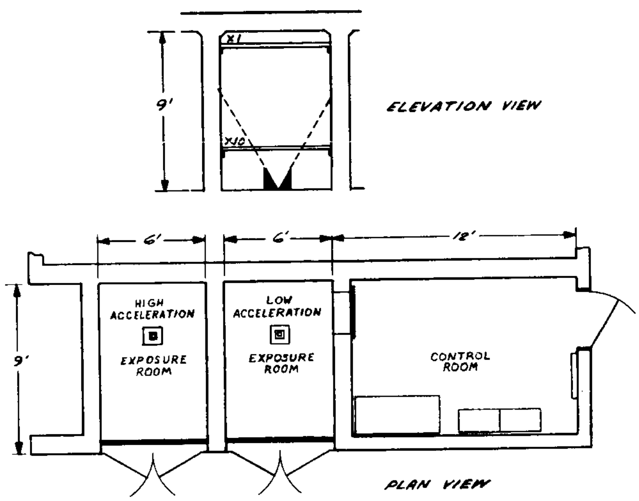


Fig. 4. JPL Accelerated Radiation Effects Laboratory

Table 3 shows the acceleration rates available with a 5 curie Ir^{192} source. To obtain a X 1 rate at the farthest distance from the source (at 2.5 meters) the radiation must be attenuated. That was accomplished using several thin lead sheets (0.033 cm each). This turns out to be a slight advantage in that a single sheet may be removed periodically to compensate for the change in dose rate due to the decay of the source (74 day half-life). However, a change to a longer-life isotope, Cs^{137} (30 year half-life), is anticipated in order to have a more stable dose rate with time at the experimental areas.

Table 3. Acceleration and Dose Rates Obtained with a 5 ci Ir^{192} Source

Distance From Source	Radiation Dose Rate	Acceleration Rate Above that at the TOPS Electronics Bay	Acceleration Rate With Attenuation by Lead Sheets
Meters	mR/hr		
2.5	456	X 4	X 1
1.5	1140	X 10	X 2.5
1.0	2750	X 24	X 6
0.75	4560	X 40	X 10
0.49	11400	X 100	X 25

A larger source is planned for an adjoining test cell which will allow accelerated testing up to X 1000, so that accelerated rates may be chosen for testing parts between X 1 and X 1000 of the radiation dose rate expected on the electronics of the outer planet mission spacecraft presently planned.

It is anticipated that the test cells will be used for long-term testing, possibly up to ten years. Therefore, the tests chosen, the test plan adopted and the environmental conditions must be planned in great detail so that useful and statistically significant data will result.

The parts which are now considered the most sensitive to radiation induced changes are semiconductor devices, since minor changes in the trapping centers and in surface ionization can produce major changes in operating conditions in these devices. Therefore, semiconductor devices of all commonly used types should be included in the test. Representative samples of various resistor types, capacitors and other active electronic components, can also be considered for long-term testing. However, past testing has shown that these device types are more radiation resistant than transistors, and they should not be included until a later phase of the long-term experiment unless they are of unorthodox construction or involve thin-film elements.

Transistors chosen from the most recent parts lists should be obtained in sufficient numbers to allow a test to be set up which has a statistical significance for the expected low rates of failure. Data analysis should include Weibull plots, since we are interested in a determination of failure predictions down to low doses and low probabilities Investigators have shown this to be a valid approach (Ref. 2).

Initial tests should be set up for times up to one year in order to determine applicable test procedures for subsequent longer term testing. Elements of the initial tests should include the following:

1. Testing at room temperature.
2. Gamma radiation exposure.
3. Powered and unpowered operating transistors in the radiation environment; and control devices in a similar, but radiation-free environment.
4. Each test group should be mounted on separate printed circuit boards to allow rapid parameter measurements.
5. The validity of removing the boards for remote measurements should be determined.
6. The test design should incorporate adequate statistical planning, so that with a limited number of specimens the most meaningful test can be carried out.

In the JPL Accelerated Radiation Effects Laboratory (AREL), the initial work is being done at the X 1 rate, because these tests take longer times. Figures 5 and 6 show the source and collimator locations in relationship to the X 1 sample locations (on the ceiling) and the X 10 location (at the table top).

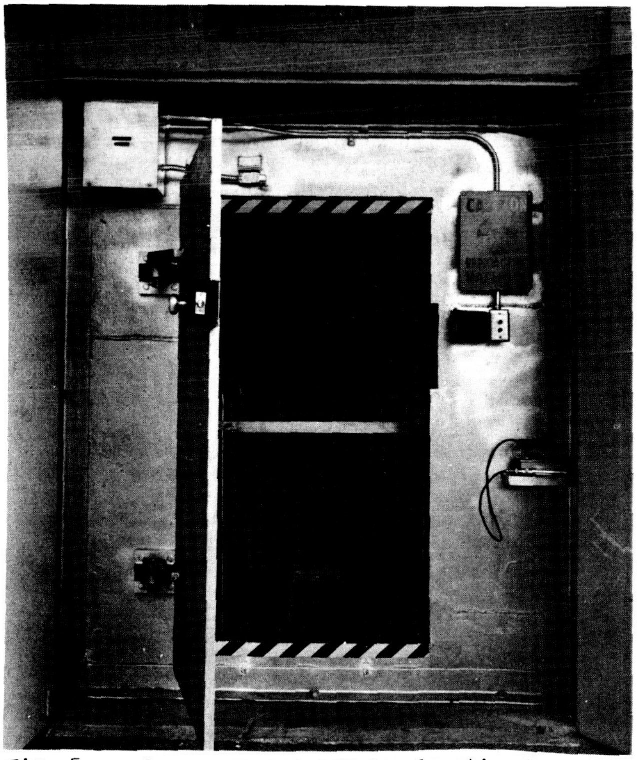


Fig. 5. Entrance to the Low Acceleration Exposure Room

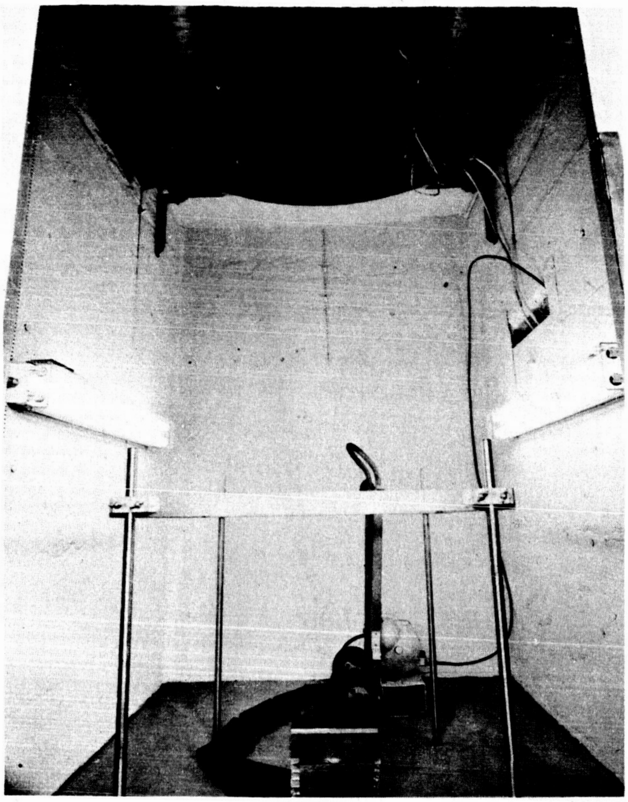
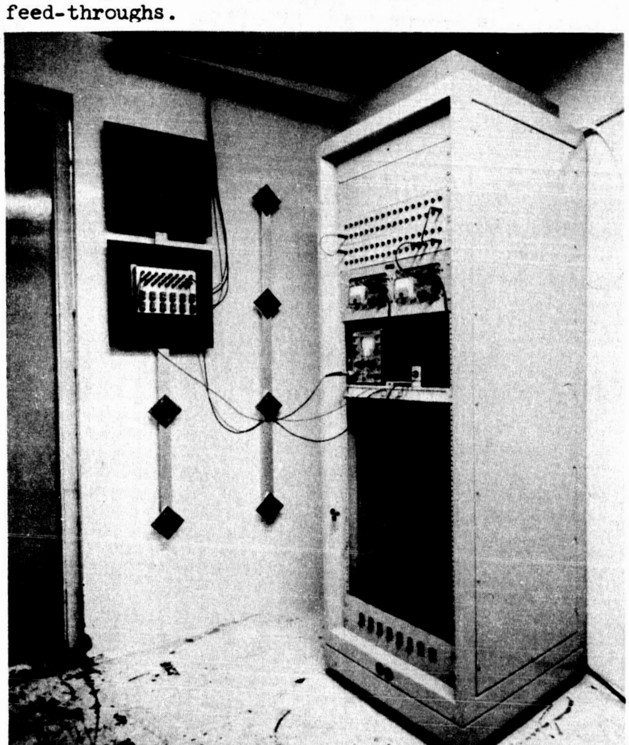


Fig. 6. Inside Low Acceleration Exposure Room

Figure 7 shows the power supplies and the test points for the integrated circuits under test and the control samples located on the wall mounting in the AREL control room. Figure 8 shows the AREL control room with the source operating mechanism, safety system and the window labyrinth for wiring feed-throughs.



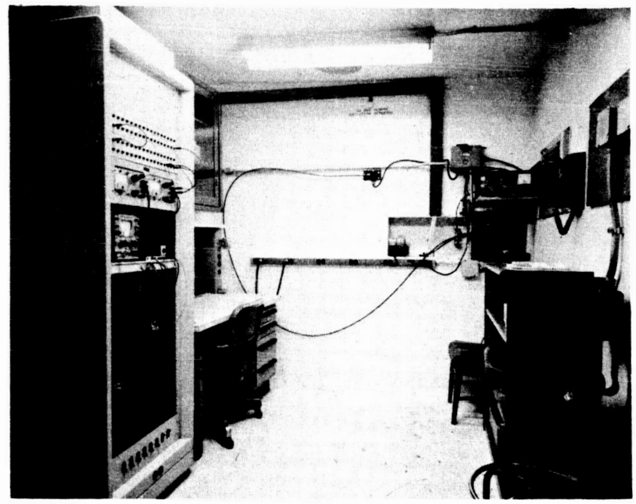


Fig. 8. AREL Control Room

CONCLUDING REMARKS

The Accelerated Radiation Effects Laboratory was constructed utilizing the design principles described in this paper and in order to confirm these principles. While the initial purpose was for testing spacecraft piece parts, the versatility allows a number of other types of experimentation to be considered, such as testing survivability of micro-organisms at low dose rates over long periods, and in vacuum. Testing of pyrotechnics and propellants is also practical in this facility and arrangements are being made to this end.

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