DESIGN CONSIDERATIONS FOR COMBINED RADIATION EFFECTS FACILITIES FOR TWELVE-YEAR OUTER PLANET SPACECRAFT VOYAGES*

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ABSTRACT

The design considerations influencing the choice and utility of environmental simulation methods and facilities are described, insofar as they relate to the new requirements imposed on outer planet spacecraft because of radiation environments to be expected. Possible means for duplicating the Radioisotope Thermoelectric Generator radiation environment, and for duplicating the effects of Trapped Radiation Belt environment are described, together with an assessment of radiation levels to be expected in the vicinity of an environmental testing chamber when in use.

INTRODUCTION

Spacecraft for outer-planet missions will depend on radioisotope thermo-electric generators for their electrical power, and on radioisotope heaters for compensatory thermal power. Since these will be fueled by Pu-238, the accompanying gamma and neutron radiation of the Pu-238 and of its daughter products will be interacting continually with the structure, systems and science experiments of the spacecraft during its many-year voyage. Super-imposed on this slowly varying background will be solar wind impingements and short duration, but higher intensity radiation stresses--namely, proton and electron irradiation when passing through the earth's radiation belts, and when passing through Jupiter's radiation belts.

In order to predict the effect of all these radiation stresses on the spacecraft and on its components, design studies for necessary predictive simulation environment facilities and for procedures are underway at this Laboratory.

The conditions under which time-accelerated testing of the effects of chronic gamma, neutron and solar wind irradiation give meaningful results must be established. The mechanisms of damage-annealing processes for different materials must be understood in some detail, since such processes are generally time dependent and temperature dependent, both of which factors become altered in accelerated testing.

The spacecraft will pass through planetary radiation belts during its voyage, and the effect of the proton and electron irradiation will be super-imposed on the on-going, chronic gamma and neutron radiation.

If there is significant alteration in the damage mechanisms in irradiated materials due to the simultaneous application of all the radiation stresses, the simulation facility should take this into account. It is practical to duplicate the complete gamma energy spectrum, the neutron energy spectrum, and the solar wind spectrum simultaneously on a specimen. It is not practical to add to this, in a cryogenic high vacuum, the very wide electron and proton spectra (1 to 100 MeV or more) that duplicate the complete radiation environment.

Such wide spectral ranges, extending to high energies, require typically linear electron accelerators and proton synchrocyclotrons. These machines do not lend themselves to combined environment testing, since they are located at separate, specialized facilities.

In order to include trapped radiation electron and proton effects in a simultaneous combined radiation effects facility, our design studies consider the validity of using lower energy electrons and protons as test fluxes. We then use an "equivalent damage" correlation for the effects to be expected from the wide range of electron and proton energies in trapped radiation belts.

The spacecraft under discussion for outer-planet trips will be designed to be usable for varying missions and purposes. The specific environments which the various outer-planet missions will encounter will have enough new features in common to justify a unified approach to the preparation of the testing facilities needed. The several different missions are depicted in Figure 1, where are shown a typical Jupiter fly-by, a Jupiter-Uranus-Neptune Mission called "JUN" and a Jupiter-Saturn-Pluto Mission called "JSP" trajectory. Each of these missions involves the use of radioisotope-thermo-electric generators for electric power; a very long (by present standards) mission-life with a corresponding high degree of reliability; and each is scheduled to pass by Jupiter, and to traverse the Jupiter trapped radiation belts.

Furthermore, most of the flights will be at a great distance from the sun with vanishingly small solar heat inputs, although the effects of the solar visible, vacuum ultraviolet, and solar wind inputs (from the early stage of the trajectory) on materials such as thermal control surfaces, will be inescapable.

All of the spacecraft in flight will be subjected to the environmental factors shown in Table I.

SIMULATION OF RADIOISOTOPE THERMO-ELECTRIC GENERATOR RADIATION

During the entire flight of the spacecraft, both gamma and neutrons are present from the on-board electric power supply: the radioisotope
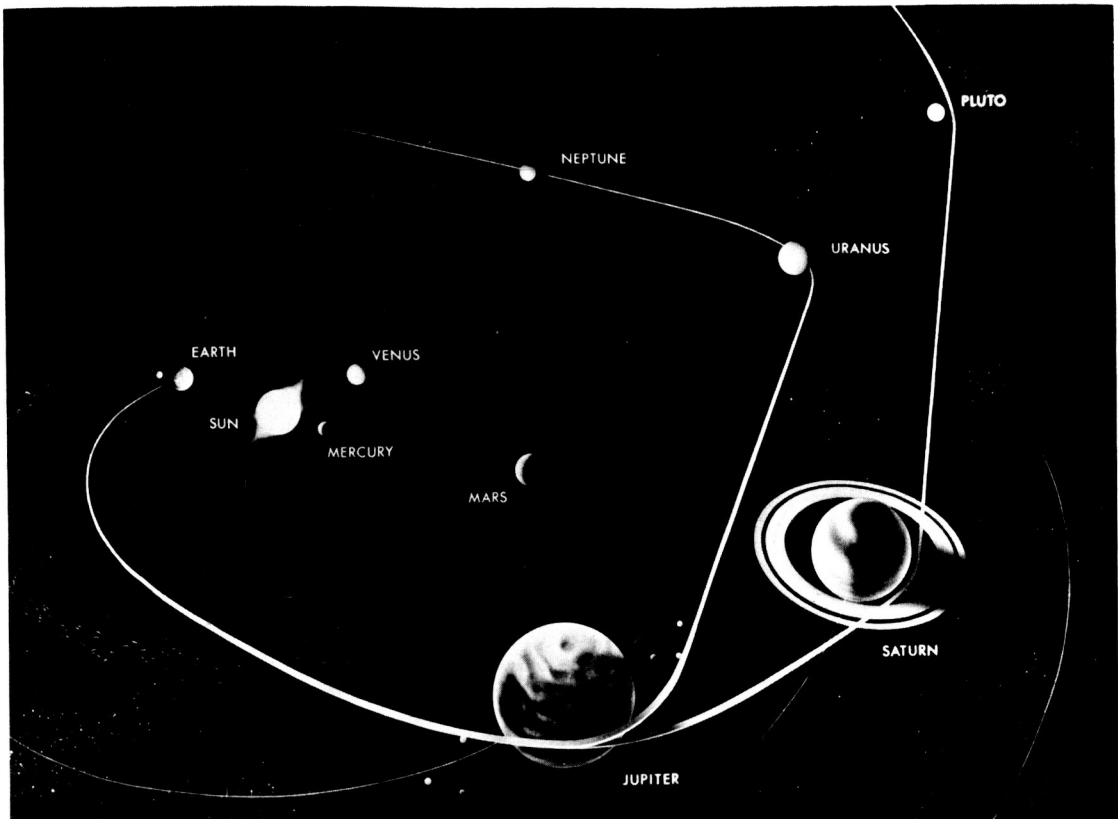
Figure 1. Typical Outer Planets Mission

Table I

Potential Combined Environment Factors
- From RTG Radiation
Gamma radiation Neutron radiation
- From Planetary Trapped Radiation Belts
High Energy Electron Flux High Energy Proton Flux
- Of Solar Origin
Visible, ultraviolet and soft X-ray
- From Conditions of Flight
Interplanetary Vacuum Space Temperature

thermo-electric generator. The effects due to the gammas and neutrons are manifested in two different ways--one effect is cumulative damage as the years go by, leading to a degradation in performance of radiation-sensitive components. The second effect is interference with operation of radiation-sensitive instruments, typically manifested as a rise in background rates of science detecting instruments.

In order to reproduce these effects, we need an accelerated source to deliver the cumulative dose to be expected in a many-year's life in a practical test time. Separately, we need a source to deliver the true rates for interference tests at the rates to be expected at various points in the trajectory.

The spectra of radiation needed for the cumulative damage studies, and for the science interference, are quite different, and are shown in Table II.

Table II

Requirements for Radiation Source Spectra		
Test	Neutron Source	Gamma Source
Cumulative Damage ($\sim10^5$ rads)	Close Spectral Match	Spectral Insensitive
Science Interference (~100 mR/hr)	Testing not Required	Close Spectral Match

For cumulative Damage Studies, we need accelerated testing to predict the effect of the proposed 12-years' exposure, and have this testing completed in a reasonable time--well before launch. We must evaluate time-intensity reciprocity failure, which involves such factors as temperature anneal and, vacuum outgassing of protective oxygen on surface films. Such evaluations and tests are

being done in a facility described in another paper at this conference (Ref. 1). Such accelerated tests can be performed on parts and on subsystems, preferably by neutrons and gammas together.

Since the gamma damage is spectrum-insensitive, any convenient gamma source may be used, conveniently either Cobalt 60 isotope or an X-ray machine. A source in the range of 150 Ci Co-60, which constitutes 2 watts of Cobalt 60, will give cumulative damage tests in a few days' elapsed time.

An accelerated close spectral match neutron source poses a problem. The actual neutron spectrum from an RTG is an α, n spectrum of Pu-238 (alpha on impurities), peaking around 3 MeV neutrons. In examining some machine sources of neutrons, we note (Figure 2) that only the d-d reaction at low bombarding particle energy gives neutrons in the few-MeV range needed for spectral match. However, Figure 3 shows that the neutron yield is unsatisfactorily low at low bombardment energies. Another higher yield possibility, sometimes considered is the reaction d, Be. When examined in detail, however, Figure 4 shows that the d, Be reaction has much detailed structure which is unsatisfactory for interpretation of test work. Seemingly, the best material is a Cf-252 spontaneous fission source, whose spectrum is shown in Figure 5, together with the neutron spectrum of a radioisotope thermo-electric generator.
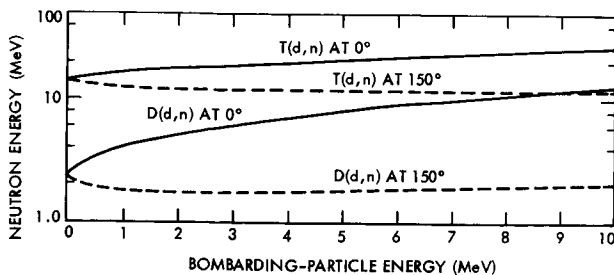

FIGURE 3   Total neutron yield per microampere of bombarding particle beam.

(From Ref. 3)

FIGURE 2   The neutron energies resulting from two accelerator produced neutron reactions vs. bombarding particle energy.

(From Ref. 3)
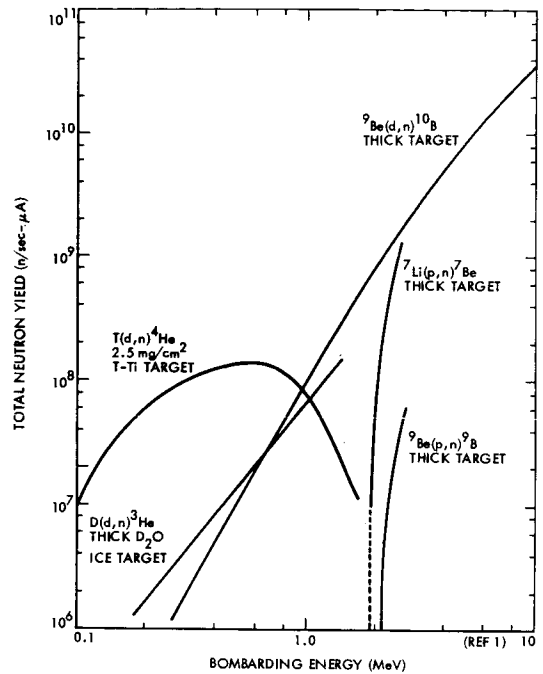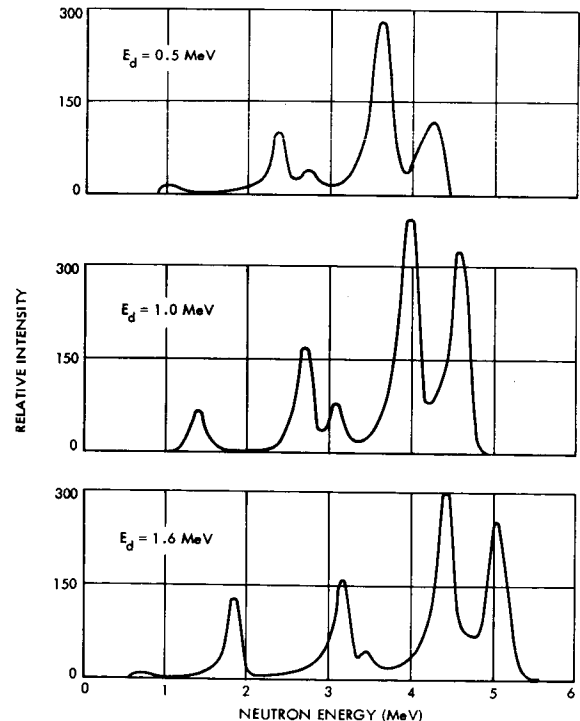
FIGURE 4   The neutron spectrum produced by deuteron bombardment of beryllium.
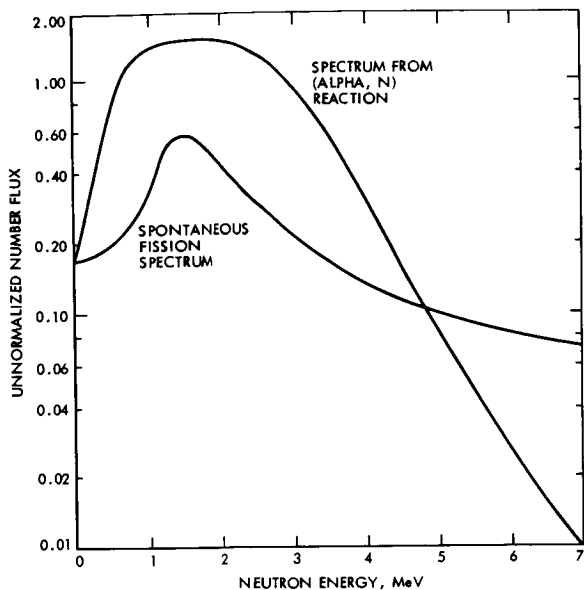
(From Ref. 3)

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Figure 5.   Comparison of Neutron Spectra

Since Cf-252 emits 2.5×10^6 spontaneous fission neutrons/second per microgram, a suitable source could consist of one milligram of this material, at a moderate cost gives 2.5×10^9 neutrons/ sec (into 4π solid angle). Such a source could deliver about 2×10^5 neutrons/cm^2 sec to the surface of a 60 cm diameter sphere circumscribing the source, requiring about ten days' exposure for a mission-cumulative dose taken as 7×10^{11} neutrons/cm^2. If the requirement for depth-dose uniformity were relaxed, or the requirement were for testing small parts, a test could be conducted at the location given by a circumscribing 20 cm diameter sphere, where only one days' exposure would be required for the 7×10^{11} n/cm^2 dose.
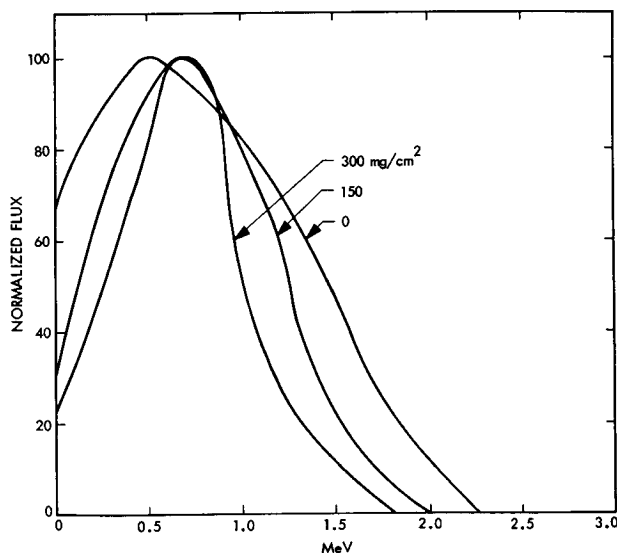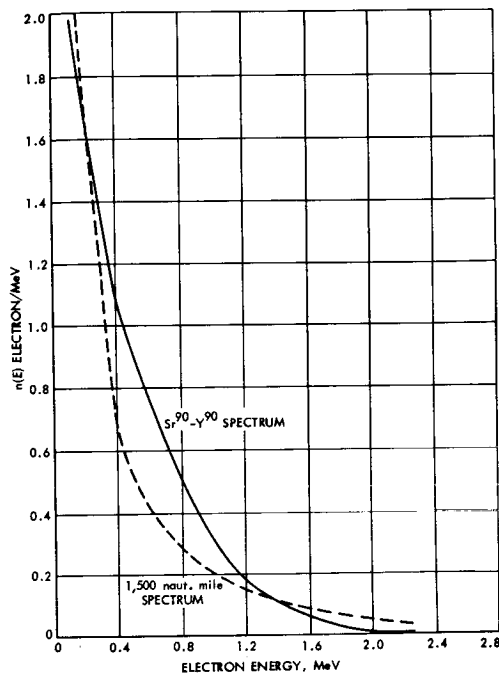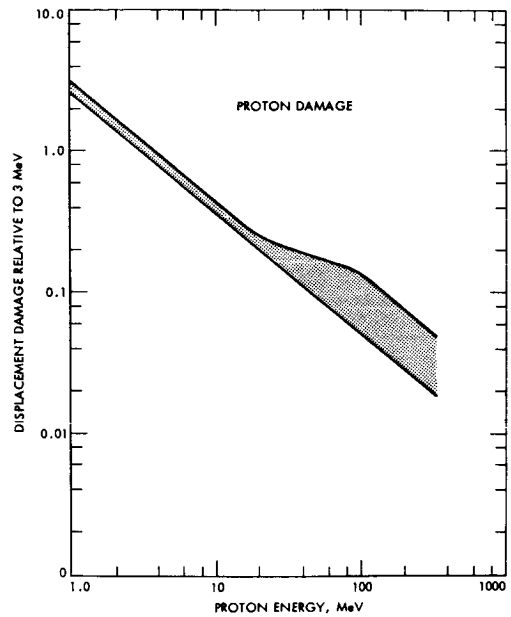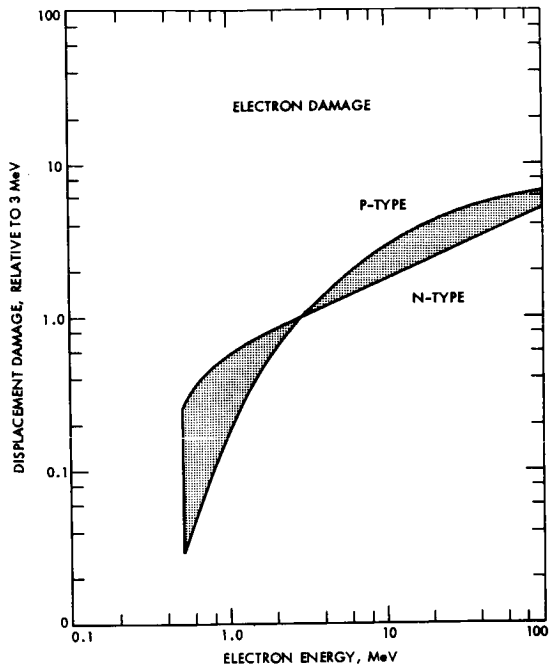
Interference

For science interference, the neutron flux of about 200 neutrons/cm^2-sec at the science platform does not give rise to any interference. The close spectral match gamma source needed, as referred to in Table II, is available, as described in another paper at this conference (Ref. 2). This close spectral match gamma source is a combination of gamma-emitting isotopes in a form that is convenient and safe to handle. The actual source can deliver up to 100 mR/hr and requires less than a curie of isotope total. This can be handled safely in a test cryogenic vacuum and solar radiation chamber.

PLANETARY TRAPPED RADIATION
BELT SIMULATION

We are here interested in sources of electrons that may be used to generate the effects of Jovian-trapped electrons, and which are usable in a combined radiation effects facility. For high energy electrons, we can consider Sr90-Y90 as a Beta source. Lutz and Newell (see Figure 6,) use this material for Van Allen Belt electron simulation. We have looked in more detail at the spectrum and find that the radiation hardens as it goes through the encapsulation of the practical source (Figure 7).

A distributed source of 11 watts of Sr90-Y90 is available to us (500 Ci), and this gives electron doses in the range of design values in one days' exposure time.   Data are available for relating radiation damage caused by electrons of a given energy, to the damage to be expected at a wide range of energies, so the damage by electrons of the energies to be actually encountered in the radiation belt can be predicted.   Figure 8 shows the actual data damage curve for the case of displacement damage to transistors.   Similar curves showing the variation of damage with incoming energy may be generated for other components as needed.

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Figure (top left): Electron Damage chart

ELECTRON DAMAGE

P-TYPE

N-TYPE

DISPLACEMENT DAMAGE, RELATIVE TO 3 MeV (y-axis, 0.1 to 100)

ELECTRON ENERGY, MeV (x-axis, 0.1 to 100)

Figure (top right): Proton Damage chart

PROTON DAMAGE

DISPLACEMENT DAMAGE RELATIVE TO 3 MeV (y-axis, 0.01 to 10.0)

PROTON ENERGY, MeV (x-axis, 1.0 to 1000)

For protons, we must use a source of sufficient energy so that the protons involved will penetrate into the bodies of components. This requires well over 10 MeV energy. An important design point is that the flux be steady and not be offered in peak pulses with the attendant rate problems, as in a synchrocyclotron.

Some information on proton damage is available as shown in Figure 9, and similar curves showing the variation of damage with incoming energy may be generated for other components as needed. For such a proton generator, we envision the use of the reaction
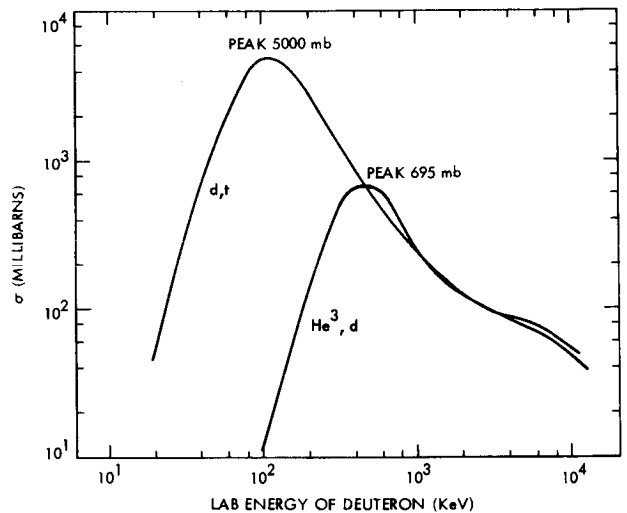
$$He^3 + d \rightarrow p + \alpha$$
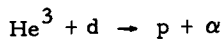
This is a mirror reaction to the well known t, d

$$H^3 + d \rightarrow n + \alpha$$
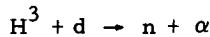
The efficiency of the process can be seen from the data in Figure 10. For comparison, we note that a d, t generator giving about 10^{11} neutrons/sec into 4π, costs about \$28,000 and such a generator would serve to give over 10^{10} p/sec when using the He^3-d reaction. Such a reaction can be run in a vacuum tank, so there is no wall to stop generated protons. We are developing a dispensing target, based on the diffusion of deuterium through a palladium thimble, which is exptected to give a long life in this usage and enable tests of trapped radiation belt protons to be feasible.

Solar Origin Radiation

Present simulation chambers are adequate for tests involving ionizing radiation insofar as space vacuum and space temperature effects are involved. It is also practical to add ultraviolet lights and solar wind sources to such simulation chambers.

Figure (middle right): cross section chart

PEAK 5000 mb

PEAK 695 mb

d,t

He^3, d

σ (MILLIBARNS) (y-axis, 10^1 to 10^4)

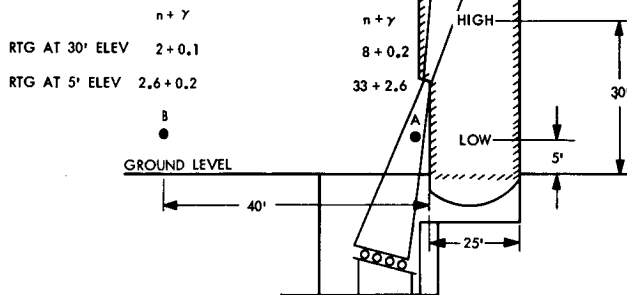LAB ENERGY OF DEUTERON (KeV) (x-axis, 10^1 to 10^4)

Conditions of Flight

Present simulation chambers have adequate provision for maintaining the vacuum condition and for holding the shroud temperatures at space temperature simulation conditions.

A calculation has been made of the radiation levels to be expected in the vicinity of a solar simulator, when a simulated radioisotope thermoelectric generator is contained therein, along with the spacecraft full scale model. Figure 11 shows the radiation levels in mrem/hr at two selected personnel working locations in the vicinity of an environment simulation chamber.

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RADIATION FIELD STRENGTHS
IN MREM/hr AT SELECTED
LOCATIONS IN VICINITY OF
25' SIMULATOR FOR RTG OF
9450 W (TH)

	n + γ	n + γ
RTG AT 30' ELEV	2 + 0.1	8 + 0.2
RTG AT 5' ELEV	2.6 + 0.2	33 + 2.6

In a similar fashion, protons from the He^3,d re-action, which have an energy of 16 MeV, can be generated inside a combined radiation effects facility to induce the effects of high energy trapped protons if the relative damage coefficients relating proton damage to proton energy are known. These must also be known or determined for every component under test.

It is concluded and design information is given, that all the above environments, together with other factors such as solar wind and vacuum ultraviolet can be added to presently available simulation chambers, and still have radiation levels in the vicinity of such chambers such that personnel can accomplish needed test tasks without exceeding permissable radiation exposure levels.

REFERENCES

1. W. E. Price, C. G. Miller and R. H. Parker "Design Considerations and Test Facilities for Accelerated Radiation Effects Testing" This Conference

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3. H. Berger, "Neutron Radiography", Elsevier Publishing Co., New York, 1965, pp. 14 ff.

4. C. G. Miller and V. C. Truscello, JPL TR 32-1427 (May, 1970)

5. R. F. Lutz and D. M. Newell "Use of a radio-isotope as an electron source in a space environment simulation chamber", IEEE Transactions on Nuclear Science, 1967

7. S. L. Greene, Jr., "Maxwell Averaged Cross Sections for Some Thermonuclear Reactions on Light Isotopes", UCLR-70522 (May, 1967)

If the radioisotope thermo-electric generator of 9450 w(th) is located as shown, five feet above ground level, the field strength at the ground plane at Location A, just outside the environment chamber is 36 mrem/hr, while at the control console, Location B, the field is 2.8 mrem/hr. Alternately, if the spacecraft model occupies the upper half of the chamber, so that the radioisotope thermo-electric generator is 30 feet above the ground plane the radiation levels are 8.2 mrem/hr and 2.1 mrem/hr at the adjacent points and control console point, respectively.

Summary

The important attributes of the radiation fields needed to carry out simulated in-flight-condition testing on outer planet spacecraft have been examined. In order to carry out testing on the effects of radiation fields interfering with on-board science instruments, it is found that only the gamma field of the radioisotope thermo-electric generator must be simulated, but that a close spectral match is needed. In order to carry out tests on the cumulative damage effects of the radioisotope thermo-electric generator field on both scientific instruments, and on electronic, propulsion and guidance systems of the spacecraft, a neutron field is needed with a close spectral match and a gamma field is also needed. The gamma field for the cumulative damage tests, however, need not be of close spectral match.

In order to simulate the Planetary Trapped Radiation Belt effects, both high energy electrons and high energy protons are needed. It is practical to use beta particles from an Sr90-Y90 source to induce the effects of trapped belt electrons if the relative damage coefficients relating electron radiation damage to electron energy are known. These must be known or determined for every component under study.