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PROBLEMS IN THE LABORATORY SIMULATION OF SPACE PARTICULATE RADIATION

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ARO, Inc.

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NOTICES

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FOREWORD

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ABSTRACT

Space particulate radiation is reviewed, the damage mechanisms are discussed, and estimates are made of the hazardous nature of the various radiation zones. The existing capability for reproducing the space environment in ground test facilities is evaluated. It is concluded that the duplication of the complete space environment is not possible but that useful testing can be accomplished with existing techniques. Research programs are proposed for the evaluation of ground test requirements.

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INTRODUCTION

The various space flight experiments conducted to date indicate that space particulate radiation, especially that produced by electrons and protons, is hazardous to man and vehicle. For example, particulate radiation contributed to the degradation of solar cell power supplies of the Explorer 6, NAV SAT 7, ARIEL 1, Telstar 1, and others (Ref. 1). Also, spurious signals have interfered with television transmission on Ranger 3, and difficulties have been encountered in the operation of the Pegasus micrometeoroid detection panels (charge storage effect) in the radiation fields. These malfunctions clearly indicate that the problem of particulate radiation should be investigated in ground test facilities.

The literature has been surveyed in an attempt to define the environment required for particulate radiation testing. In this report, the energy and flux rate of particulate radiation required for laboratory testing and the techniques available for producing this radiation are summarized. An evaluation of the experimental work needed for the further development of particulate radiation test chambers is presented. Subject areas considered include (1) the effect of other space environmental parameters in determining the radiation damage in ground test chambers, (2) particulate irradiation techniques, (3) accelerated testing, and (4) in situ damage measuring techniques.

Although this report is the result of an extensive literature search, it is not purported to be an exhaustive state-of-the-art survey; and no attempt was made to produce a definitive engineering feasibility study. There are numerous references to the work of others which are applicable to both theoretical and hardware developments; but the principal emphasis was placed on the exploratory discussion of fundamental problems to be considered in obtaining reliable engineering data for predicting the behavior of present materials and the improvement of radiation resistance.

Flight experiments can provide data on a particular material; but they are not suitable for conducting studies of defect structures, mechanisms, and materials improvement problems. These studies must be made in the laboratory.

SECTION II
THE PARTICULATE RADIATION ENVIRONMENT

Definition of the particulate radiation environment in space from satellite data is a complex experimental task. An average environment should be mapped in space so that at each point in an orbit the particles, and the energy and flux spectrum of the particles as a function of direction, will be known. All that can be expected in the near future is an approximation of this information for regions of current interest. One of the more useful summaries of this information was prepared by Radiation Effects Information Center of the Battelle Memorial Institute and is shown in Fig. 1 (Ref. 2). In this graph the radiation is identified, and the particle flux at each energy level is given. The radiation is classified as trapped radiation, solar wind, auroral radiation, solar flares, and cosmic rays.

2.1 TRAPPED RADIATION

Many charged particles exist within the region of space permeated by the earth's magnetic field. Some of these particles spiral around the lines of force of the earth's magnetic field, and oscillate back and forth between mirror points (reflection points) in the northern and southern hemispheres. While executing this path, the particles drift either east or west around the earth depending on the charge of the particle. These particles are referred to as trapped (Van Allen) radiation (Fig. 2, Refs. 3, 4, 5). It is difficult to rigorously define this radiation, but in general it refers to particles that execute at least one oscillation between the upper and lower hemisphere and have an energy of over 1000 electron volts (ev). Particles are continually entering and leaving the trapped radiation zone, and their intensity varies with solar activity.

The trapped radiation zone includes an inner and outer belt of radiation. The inner belt extends from about 400 to 9600 km in altitude above the earth, and the outer belt is from 9600 to 64,000 km above the earth. The negative particles are electrons, and the positive particles are approximately 99-percent protons — approximately 0.5-percent deuterons, approximately 0.5-percent tritons, and less than 0.1 percent of alpha particles. Current estimates of the flux and energy of the protons and electrons are shown in Fig. 1. The energy of these particles is measured in terms of the electron volt which is the equivalent of 1.6×10^{-12} ergs or 1.6×10^{-19} joules. These particles have an energy range of from 4×10^4 ev to 10^8 ev and a flux range of from about 20 to 2×10^9 particles/cm^2/sec.

2.2 SOLAR WIND

There is a flow of charged particles, principally protons, outward from the sun, which is called the solar wind. However, there is also a small concentration (~1 percent) of alpha particles. The kinetic energy (Fig. 1) range for these particles is from $\sim 3 \times 10^2$ to $\sim 6 \times 10^3$ ev with a corresponding intensity variation of from 10^8 to 10^{12} particles/cm^2/sec. The bulk velocity of this stream varies from about 300 to 800 km/sec (Refs. 6 and 7).

Results from the Mariner-Venus probe (Ref. 7) indicated bulk velocity variations from 320 to 770 km/sec. The average plasma temperature, as would be measured in a frame of reference moving with the plasma, was estimated to be 10^5°K (~13 ev). Although velocity variation did show some correlation with terrestial magnetic activity, attempts to extrapolate velocity variation back to recognizable features on the sun were unsuccessful. The majority of the particles had an energy between 750 and 2500 ev, they are found throughout interplanetary space, and, as is shown by the Mariner-Venus measurement, the flux density varies inversely with the square of the radius from the sun.

2.3 AURORAL RADIATION

Auroral radiation (Ref. 6) may affect space vehicles that pass over the polar regions of the earth. (This radiation interacts with atmospheric constituents with a resulting emission of light (seen at magnetic latitudes of about 65 to 70 deg). It occurs from 80 to 1120 kilometers above the earth and is composed of electrons and protons, but its origin is not known. The electrons vary in energy from 8×10^3 to 7×10^4 ev with corresponding flux rates of 2×10^{11} to 1×10^6 particles/cm^2/sec. The proton energy ranges from 7×10^4 to 1×10^6 ev with flux rates from 10^6 to 10^2 particles/cm^2/sec.

2.4 SOLAR FLARE PROTONS

The solar flare protons (Ref. 8) originate on the sun and are considered to be a major hazard in interplanetary space. These particles are ejected from the sun during a solar flare.

The general features of a solar flare are as follows:

1. Light is emitted consisting of monochromatic radiation characteristic of such elements as hydrogen, helium, calcium, iron, and silicon.

2. Radio frequency emission occurs simultaneously with the optical emission. There are several classes of radio frequency (RF) emission, the more important of which are Type-IV. This radiation has been correlated with the production of solar flare protons and the arrival of these particles at earth. This RF emission is thought to be from electrons accelerated during the flare that are trapped by local magnetic fields.

3. Particles from the flare are emitted simultaneously with the optical and RF radiation. These particles are predominantly protons, but apparently a small and varying amount of heavier particles is always present. The heavier particles are predominantly alpha particles, but nuclei in the CNO group are present. These particles arrive at the earth from a few minutes to several hours after the maximum light emission from the flare. The energy of the protons varies from a few thousand electron volts to perhaps 10^{10} ev, with corresponding flux rates of 10^{6} to 10^{-1} protons/cm^{2}/sec. The energy and intensity of protons from both a typical and an intense flare are shown in Fig. 1. The intense solar protons do not correlate strongly with the maximum in the 11-year cycle of solar activity. These events appear to occur during either the increasing or decreasing period of the solar activity cycle and have a frequency of about one event every 18 months. A summary of the integrated flux for some of the larger events is shown in Table I.

4. One or two days after the solar flare, a plasma ejected from the sun during the flare arrives at the earth. This plasma carries with it the magnetic flux that bound it together in the vicinity of the sun. The arrival of this plasma produces changes in measured values of the earth's magnetic field and the cosmic ray intensity. Aurorae and ionospheric disturbances are also observed during this period.

2.5 GALACTIC COSMIC RAYS

Galactic cosmic rays (Refs. 2 and 6) include all high energy particles that presumably originate within our galaxy with the exception of the solar flare protons. The origin of these particles is presumed to be from the stars and from stellar explosions in our galaxy; however, extragalactic sources must be considered as a possible contributor to the cosmic ray flux. The principal particle is the proton, although there is an alpha particle composition varying between 5 and 15 percent. Also, there is a small fraction of a percent of other nuclei such as boron, lithium, and beryllium. The energy range of these particles is approximately 10^8 to 10^{20} ev, and the flux rate appears to be always less than 1 particle/cm^2/sec. Because of the low flux rate of these particles, cosmic rays, as we are now able to describe them, will not present a major radiation hazard.

2.6 MAN-MADE RADIATION

Military and scientific applications of nuclear explosions in space can produce intense sources of radiation. The radiation that results from such explosions will either be dissipated out into space from the center of the explosion or, if the location of the explosion is favorable, trapping of the radiation will occur. The particles that can be trapped are the electrons and protons, which are produced as follows:

1. Emission of energetic electrons by fission fragment decay.
2. Decay of a neutron from the explosion into a proton and an electron.
3. Interaction of γ rays from the explosion with the constituents of the atmosphere to produce electrons.

Since they have no charge, the neutrons will not be trapped. Some of these particles will escape from the trapping zone before they decay into charged particles. The energy of the electrons from such an explosion will vary from a few hundred thousand electron volts to about 8×10^6 ev. The protons will have an energy of approximately 10^6 ev.

A series of high altitude explosions (Ref. 6) was planned in 1958 to utilize these charged particles to study the trapping of such particles in the earth's magnetic field. These were the Argus I, II, and III experiments of August and September of 1958, which were planned prior to the discovery of the Van Allen radiation belts. In addition to these experiments, there were two other high altitude explosions by this country and three by the U.S.S.R. between August 1958 and November 1962. The only one of these events that produced a significant change in the trapped radiation was the Starfish explosion of July 1962. Only the electrons remain from this explosion, and they are between 0.25 and 0.7 earth radii above the earth's surface (Ref. 2). The electrons have decay constants (the time required for the intensity to decay to 1/e of the initial value) as high as three years. The results from these explosions indicated that the particles in the inner belt had a longer lifetime than the particles in the outer belt.

SECTION III
DAMAGE POTENTIAL OF SPACE RADIATION REGIONS

To determine the particulate radiation requirements for ground testing, potential radiation hazard regions must be identified. These can be estimated from a survey of the mechanisms that create damage in materials and of actual damage incurred by materials from electron and proton bombardment. In the absence of data on damage in material by proton and electron bombardment, damage from these particles may be inferred from damage produced by nuclear radiation. Material damage is produced by the following mechanisms: (1) displacement of atoms from the crystal lattice, (2) ionization of atoms in the crystal lattice, and (3) nuclear reaction.

Damage is considered herein to be any change in the engineering properties of a given material which impairs its intended function. The number and energy of incident particles required to produce damage will be a function of the material.

3.1 ATOMIC DISPLACEMENT

The energy an atom must receive from a charged particle to be removed permanently from its lattice position into an interstitial lattice position has been estimated to be about 25 ev (Ref. 9). The displacement energy for a typical atom in a tightly bound solid was assumed to be approximately five times the sublimation energy (~5 ev) of the atom. It is highly unlikely, because of the nature of this process, that for a given material there will be a specific energy value above which displacement will always occur. Probably there will be a range of energy values (Ref. 9) over which this will occur for each material. The average of these energy values, referred to as the displacement threshold for a given material, varies from approximately 10 to 30 ev for various materials (Ref. 2). If this is true, then there should also be some average energy of a charged particle that will produce a displacement in a given material. This information and its relation to space radiation is summarized in Table II and Fig. 3, where A refers to the atomic weight of the materials being irradiated. As is shown in Table II, space radiation will damage materials by displacement to whatever depth the particle is able to penetrate and still transmit the necessary energy to the lattice atoms. This damage will result in changes in the structural, thermal, electrical, and optical properties of the irradiated materials.

To estimate the time period for material damage to occur, one must know the average frequency at which these events occur per irradiating charged particle and the number of such events required to produce a significant change in the engineering properties of materials. This information is not available since proton and electron damage studies have been made on only a few engineering materials, and since space probes have not yet been returned to earth for inspection after extended periods in space radiation regions. However, much information is available on material damage as a result of studies in the nuclear energy field (Refs. 10 through 17). The results of radiation damage studies in the nuclear energy field could be used to calculate particulate radiation damage if a correlation could be developed between them. Unfortunately, very little progress has been made in this direction. One of the initial attempts to produce such a correlation is shown in Table III for transistors and diodes. This information is very limited and is, at best, only an approximation that should be used in the absence of particulate radiation data.

An attempt to use from the nuclear energy field radiation data for predicting the time required to produce damage by space particulate radiation is shown in Fig. 4 (Ref. 16). The fraction of displaced atoms required to produce damage (based on nuclear radiation damage) is shown with the estimated fraction of displaced atoms per year that would occur in the various radiation regions. A comparison of the values shown indicates that classes of materials such as ceramics, metals, and semiconductors will be damaged by the trapped and solar radiation. Cosmic rays will not produce significant damage except over a period of hundreds of years.

To determine if the irradiation time required to produce damage as calculated from Fig. 4 can be considered to be at least a reasonable estimate, some specific cases of irradiation time for particulate radiation damage obtained in ground test facilities were transformed into equivalent times for the trapped radiation region. In Table IV these values are compared with time intervals calculated from Fig. 4. Table IV shows that ground test irradiation times fall well within the limits obtained from Fig. 4, but it is also clear that the limits obtained from Fig. 4 are so broad that they are quite useless in predicting the irradiation time for a given material by a particle at a fixed energy level. Since there is no proven correlation at the present time between nuclear and space radiation damage, this information cannot be applied with any confidence in the design of spacecraft. Engineering data for particulate radiation damage must either be obtained in the laboratory or from space flight experiments. Until this information becomes available for all materials being considered for space applications, the lifetime of various materials in the space radiation field cannot be predicted.

3.2 IONIZATION

Ionization occurs when a charged particle strikes a material and knocks an electron free from one of the atoms in the material. The electron energy required to produce ionization in a material is extremely small, 20 to 25 ev (Ref. 2). Consequently, all known electron radiation in space (Fig. 3) will produce ionization in materials to whatever depth the electron is able to penetrate and transmit this amount of energy to atoms of the material.

The proton energy required to produce ionization is a function of the target material and is approximately equal to (1000 A) ev. A is the atomic weight of the material. As is shown in Fig. 3, all proton radiation in space, with the exception of the solar wind, will produce ionization on the surface and in the interior of the material that it penetrates.

3.2.1 Ionization Damage

Ionization will cause permanent damage in organic, ionic, and ceramic types of materials. Human tissue is, of course, in the organic class. Damage in organic material is caused by the degradation and cross linking of molecules. The degradation of the molecules results in a lower molecular weight, free radicals, trapped gas, decrease in material strength, and a higher vapor pressure. Crosslinking results in an increase in average molecular weight and viscosity. Ionic solids, such as the alkali halides, undergo damage from the formation of color centers which reduce the optical transmission of the material. Similar damage is observed in glass.

Estimates of damage (Ref. 16) to material by ionization, based on radiation damage in the nuclear energy field, indicate that the absorption of energy equivalent to 10^{16} to 10^{24} ev/gm will produce an appreciable change in the engineering properties of plastics (Teflon®, nylon, phenolic, etc.), elastomers, oils, grease, ceramics, and, most important of all, the human body. Materials such as metal and semiconductors will not be permanently damaged. Since the particle range in many of these materials, and hence the energy absorption per gram of material, is not known, it is impossible to predict the energy per gram absorbed in each of the space radiation regions. However, it can be shown that energy will be transmitted to these materials by space radiation of the same order of magnitude as the estimated absorbed energy per gram (10^{16} to 10^{24} ev/gm) required to produce damage by nuclear radiation. For example, the trapped radiation region will transmit energy equivalent to 10^{16} to 10^{22} ev/cm^2/yr. Over a period of a year, the energy transmitted by other radiation regions will consist of 10^{16} to 10^{23} ev/cm^2 from auroral radiation, 10^{16} to 10^{17}

ev/cm^2 from solar flares, and 10^{15} to 10^{16} ev/cm^2 from cosmic rays. If the extrapolation from nuclear radiation is valid and if this energy is absorbed per gram, then ionization from space radiation can be considered as damaging to some materials and also to man since his threshold limits fro damage are 10^{16} to 10^{17} ev/gm.

3.3 NUCLEAR REACTION

The most general definition of nuclear reaction (Refs. 20 and 21) refers to the process that occurs when two nuclear particles come in close contact. In space, the process that is important is the one in which a charged particle comes in close contact with the nucleons of a spacecraft material atom. This process produces damage by creating impurities in the material. This reaction can be better understood if the possible life history of a single particle penetrating the nucleus is discussed. Some of the possibilities are as follows:

1. The particle may be elastically scattered. If this occurs, the nucleus remains in its initial state, and the particle emerges from the nucleus without any change in energy.
2. The particle may be inelastically scattered. In this case, there is an exchange in energy between the particle and the nucleons, and the particle emerges with a different energy and leaves the nucleus in an excited state.
3. The energy transfer between the particle and nucleons is large enough to eject one or more nucleons from the nucleus.
4. The transfer of energy from the particle to the nucleons is large enough to prevent the particle from leaving the nucleus. There is a continuing exchange of energy between all nucleons and between the particle and the nucleons leaving the nucleus in an excited state. In this state, the escape of a particle is possible only by accidentally accumulating sufficient energy through an energy exchange with the other nucleons; and when in this state, a compound nucleus is said to exist. The excited nucleus may decay by emitting a nucleon, or by emitting radiation and reducing the energy level such that no nucleon may escape.

Events (3) and (4) transmute the parent atom and produce impurities. Event (3), sometimes called spallation, is more likely to occur with particle energies above approximately 40 Mev, whereas event (4), compound nucleus formation, is more probable at energies below 40 Mev.

Although sufficient information is not available to define a general proton energy threshold for damage to engineering materials, a reasonable value may be inferred by examining some very limited results on the more sensitive materials, such as human tissue and silicon. In the case of human tissue, 10 percent of the total damage incurred by the tissue from irradiation with 10^8 ev protons is by transmutation (Ref. 6). It has also been estimated (Ref. 2) that the damage to silicon by nuclear reaction will become significant with respect to that incurred by other damage mechanisms at proton energies of 10^8 ev. Other sources (Refs. 18 and 22) indicate that this damage will become significant in silicon at proton energies of from 1.8 to 4.5×10^8 ev. If this limited data on the more sensitive materials is an indication of a lower limit for this type of damage, then protons with energies below 10^8ev will not produce appreciable damage by nuclear reaction. Consequently, if this is substantiated by further experimental work, only the intense solar flares and cosmic rays would have sufficient energy to produce this type of damage. Available information on cosmic ray flux rates indicates that engineering damage will not result from these particles, since the rate of impingement is so low, approximately one particle/cm^2/sec. However, the intense solar flare is sufficiently severe to be considered a radiation hazard and to produce damage by nuclear reaction. Fortunately, the average frequency of intense flares per year, from present estimates, appears to be approximately one, but it is also possible to accumulate with one flare considerable damage even though its maximum duration is generally less than two days. Insufficient information is available on nuclear reactions produced by high energy protons, and evaluation of the damage potential from this source must be made in the laboratory.

3.4 SUMMARY OF DAMAGE POTENTIAL

Consideration of the radiation damage mechanisms indicates that simulation of cosmic rays will not be a test requirement because of the low flux rate estimated for particles. If flight data should ever indicate a higher flux rate, simulation of cosmic radiation may become a requirement. The damage potential from all other space radiation, on the basis of present information, is severe enough to require simulation in ground tests. This information is summarized in Table V.

SECTION IV
SIMULATION OF PARTICULATE RADIATION PARAMETERS

To evaluate the feasibility of ground testing, the current capabilities for simulating the various space parameters must be reviewed. The particulate radiation parameters of interest are the energy and flux rate spectrum of the electrons and protons. In addition, other environmental parameters such as radiation heat sink of space, vacuum, molecular population, and solar radiation will be reviewed as possible constituents of the particulate radiation ground test environment.

4.1 PARTICLE ENERGY

Electrons and protons can be accelerated in the laboratory to energies found in the space radiation fields except for the extremely energetic cosmic rays. All radiation required for ground testing (Section 3.4), except for the intense flare, can be produced in the laboratory by conventional generators with energy capabilities of 10^8 ev or below (Fig. 5). The intense flares will require specialized equipment with energy capabilities up to 10^9 ev.

The low energy electrons and protons can be produced by electron guns and ion sources (Ref. 23). The energy range of these sources is from a few hundred electron volts to energies of the order of several hundred thousand electron volts. Potential drop and linear accelerators, and cyclotrons easily cover the range from this level up to 10^8 ev. The region from 10^8 ev up to 10^{10} ev can be covered only by highly specialized equipment such as the cyclotron and synchrotrons.

4.2 FLUX RATE

The flux rate simulation problem can best be discussed from the standpoint of the basic particle generators exclusive of external beam loses since these will vary with the application and design of a specific generator and delivery system. The low energy space radiation with flux rates of 10^8 to 10^{12} particles/cm^2/sec can be generated by the electron guns and ion sources. These devices have current capabilities of the order of 10 to 20 ma or higher, which is the equivalent of approximately 6 to 12 m^2 of area being irradiated at a flux rate of 10^{12} particles/cm^2/sec. Consequently, both large and small scale testing are possible in this energy range.

Particle flux intensities corresponding to the intensities found in space for particles of about 10^5 ev energy and higher can be generated by potential drop and linear accelerators, cyclotrons, and synchrotrons. These accelerators are, in general, capable of currents from a fraction of a microampere to hundreds of microamperes (Refs. 24 and 25). That this output is sufficient for useful simulation can be shown by a consideration of the space flux rate requirements for this energy range. The flux rate requirements vary from 10^9 particles/cm^2/sec at 10^5 ev to 10^6 particles/cm^2/sec or lower at 10^8 ev. Approximately a 20μa beam current is sufficient to irradiate approximately 12 m^2 at a flux rate of 10^9 particles/cm^2/sec. Since the other flux rates for a corresponding area would require only a fraction of a microampere of beam current, flux rates can probably be produced for large and small scale irradiation work with monoenergetic beam generators.

4.3 ENERGY AND FLUX RATE SPECTRUM

In general, the proton and electron flux at a given point in space consists of a range of energies with a certain flux rate associated with each energy. Accelerator development in the past has been directed toward producing higher energy monoenergetic particle generators for basic research and not toward developing a generator to produce a beam with an energy spectrum for space radiation testing. Consequently, the simultaneous simulation of this spectrum is not possible at the present time. An extensive development program will be necessary if such a generator is ever required for testing.

4.4 OTHER ENVIRONMENTAL PARAMETERS

Other parameters in the space environment which, by their presence or absence in ground test facilities, may influence the results of particulate radiation testing, are the radiation sink of space, vacuum, molecular population, as well as solar electromagnetic radiation, planet albedo and planet emitted radiation.

4.4.1 Radiation Heat Sink of Space

The star-background of space constitutes a heat sink equivalent to a blackbody at a temperature of about 4°K. True simulation of this condition could be achieved if the test chamber walls were maintained at 4°K and were completely nonreflective, but this is not economically feasible. Simple radiative heat balance calculations, however, demonstrate that only a small error in the test vehicle temperature will result when the chamber walls are 80°K rather than 4°K as long as the vehicle temperature is above 200°K. The results of some of these calculations are summarized in Table VI to illustrate the size of these errors.

The space heat sink would be simulated by liquid-nitrogen-cooled cryopanels which would be painted black to minimize back reflections. Although these surfaces may initially be good radiation absorbers, the accumulation of cryodeposits during long duration tests may alter their reflection characteristics (Ref. 28). In some cases, if the temperature errors introduced to the test material effect its annealing properties, some special techniques in the form of model cooling or colder chamber walls may have to be employed. However, this degree of approximation for simulating the star background should be sufficient for most radiation damage tests.

4.4.2 Solar and Thermal Radiation

In general, solar electromagnetic radiation will have two effects on the test article: (1) it will supply thermal energy to the model, and (2) some wavelengths will have sufficient energy to rupture chemical bonds and create damage to material in the model. These effects can be expected to influence the results from particulate radiation bombardment: the first by altering the annealing effects and the second by rupture of particular chemical bonds.

For certain earth orbit positions, the albedo and earth radiation can represent a heat load to the vehicle comparable to that caused by direct solar radiation. This thermal radiation may also influence particulate radiation damage mechanisms in the same manner.

Simulation of solar and thermal radiation (Refs. 29 and 30) has proven to be a very challenging problem. A recent survey of the current state-of-the-art has been made by Latvala and Birkebak (Ref. 31). The degree of simulation of electromagnetic radiation depends upon the type of test being conducted. For some tests it is conceivable that only thermal energy need be duplicated; but, more generally, some simulation of the spectral distribution will be required. Table VII lists the chemical bond dissociation energies of molecules of interest.

Molecules with bonding energies of about 3 ev, for example, would be ruptured by electromagnetic radiation having wavelengths less than 4×10^{-5} cm. The energy of the radiation in this region increases with decreasing wavelength such that at a wavelength of 5×10^{-7} cm the energy has reached a level of approximately 240 ev. In view of this, it would appear necessary to approximate the spectral energy of the sun in this region reasonably well to determine realistically the damaging effects of electromagnetic and particulate radiation in the laboratory.

Several types of solar simulators are in use; however, long term reliable operation has not yet been achieved with most of these systems. Radiant energy sources commonly used in these systems include carbon arcs, xenon lamps, and mercury-xenon lamps. Of these the carbon arc provides the better spectral match at wavelengths between 4×10^{-5} cm and 3×10^{-4} cm but has more severe operational problems (Ref. 31).

Although the wavelength range below 4 x 10^{-5} cm may be of interest there is no single source that can reproduce the spectral energy of the sun at these short wavelengths.

Simulation of albedo and planet emitted radiation involves so many more varying parameters and as yet unknown factors which define the environment that a sophisticated simulation of these conditions has not as yet been seriously attempted. At present only the thermal energy is simulated in large space simulation chambers. Actually the spectrums of these radiations are not fully known.

Small scale laboratory tests would be useful in determining the importance of spectral match for both direct solar simulation and the planet induced thermal radiations. Such an investigation might also be designed to measure the consequences of spectral mismatch.

4.4.3 Vacuum and Molecular Population

The feasibility of reproducing the vacuum and molecular species found in space depends on: (1) capability of producing operating pressures of 10^{-6} to 10^{-14} torr, (2) maintaining the specific molecular population at these pressures which exists in solar space, and (3) elimination of test chamber contamination.

Pressures in the 10^{-4} to 10^{-14} torr range can now be produced although no large scale chambers, such as the AEDC Mark I chamber and the NASA-Houston Chamber A, are known to be operating below 10^{-8} torr. However, many smaller chambers have this capability. One such test chamber was pioneered by H. Mark and R. D. Sommers at the NASA-Lewis Research Center (Ref. 27).

The exact duplication of the solar space molecular population in a test chamber would be quite difficult, particularly with respect to reproducing the ionized particles. The necessity of exact simulation of this environment, however, is not yet clear and will have to be determined experimentally together with an evaluation of some of the problems of simulating the specie population. Elimination of test chamber contaminants (absorbed gases, pump oil vapor, etc.) should be emphasized. Practically speaking, this probably can't be done completely, but it should be possible to reduce contaminants to an acceptable level by the proper selection of materials, reduction in outgassing by cryogenic cooling, and the use of high vacuum techniques in chamber construction. The return of outgassing and leakage constituents from the chamber walls can be also minimized by having an efficient pumping configuration at the chamber wall.

It is difficult to specify the effect that extremely low pressures and a specific molecular population will have on particulate radiation damage. However, since this environment will be of principal importance in determining the amount of the molecular population adsorbed on the test article surface, and the rate of sublimation of the surface material, undoubtedly it will be of interest primarily in determining surface effects from particulate radiation.

4.4.4 Status of Ground Simulation Capabilities

A review of current capabilities indicates exact simulation of all parameters of interest in the space environment is not possible (see Table VIII).

SECTION V
DEVELOPMENT OF IMPROVED TEST TECHNIQUES

Early particulate radiation testing in support of the space effort was generally started before much information was available on the space environment. Consequently, test conditions were not controlled, nor was there any great effort to duplicate space conditions. Most of this work was done under atmospheric conditions or under a mild vacuum. Using past radiation work in the nuclear energy field as a guideline, exploratory testing has indicated areas of weakness in systems and materials, and has aided in the initial development of radiation resistant materials for use in space. However, more complete and reliable engineering information is now needed for the design of manned space vehicles and advanced unmanned space probes that will stay for long periods of time in particulate radiation fields. The development of advanced testing techniques and second generation engineering test facilities is needed to support these missions. The importance of the following areas to testing in ground facilities must be determined in order to develop these advanced facilities: (1) synergistic effect in radiation damage, (2) flux rate effects on damage, (3) mode of irradiating test article, (4) test chamber molecular population, and (5) in situ damage measurements.

5.1 SYNERGISTIC EFFECTS

An understanding of the extent to which the damage from particulate radiation is influenced by the presence of other environmental parameters is important in determining if these parameters have to be simulated in ground facilities. This area of investigation is referred to by some workers (Refs. 33 through 39) as the determination of synergistic effects. Early synergistic tests were limited in scope, and the true significance of synergistic effects is yet to be determined. Improvement of test techniques will result from:

1. Use of in situ techniques to measure damage.
2. Adequate control of test article temperature during testing and damage measurements.
3. Evaluation of the effect of particle flux rate.
4. Adequate control of system contamination and molecular background.
5. Inclusion of all synergistic parameters within a given test.
6. Reporting test results clearly so that comparisons can be made between the various investigations in this field.

One of the earliest synergistic studies was that of Denny and Hammel (Ref. 34), reported on early in 1963. This investigation was a study of the effect of vacuum and ultraviolet radiation on mylar, white paint, anodized aluminum, and solar cell covers. Synergistic damage effects were noted on some of these materials. However, the individual effects of the various parameters were not determined; only the combined effects were measured, and in situ damage measurements were not made on the samples. A radiation intensity higher than that found in space was used throughout these tests, and the influence of intensity on radiation damage was not evaluated. Intensity of radiation was not monitored or controlled during tests. Pressure, a test parameter, was not varied to determine its effect on damage, there was no attempt to produce a specific molecular test population, and system generated contaminants were not controlled or monitored.

Denny and Hammel point out these limitations in their report (Ref. 34) as a guide to other investigators.

In 1965 Breuch (Ref. 35) carried out synergistic studies with electron and ultraviolet radiation for various thermal coatings. Some of the same limitations apply to this work, including: (1) in situ damage measurements were not used, (2) control of sample temperature was not adequately defined, (3) the intensity of flux rate of the ultraviolet and electron radiation was not defined, and (4) the background molecular population was high and not defined or controlled.

Early in 1966 Pinson (Ref. 40) investigated the individual and combined effect of vacuum, ultraviolet radiation, and electron radiation on three thermal control coatings. Some of the same limitations apply in that in situ damage measurements were not made, variation in sample temperature during a run was not defined, and the molecular background during the tests and its possible effect on the damage of the test specimens were not defined.

Investigators should take advantage of the work mentioned here and evaluate their experimental procedures so that the completeness and validity of their synergistic test results will be insured.

The work of Farnsworth (Ref. 37) indicates that in situ damage measurements are essential, and a comparison of the work of Pinson (Ref. 40) and Campbell and Miller (Ref. 39) indicates the importance of considering the effect of flux rate on damage in planning an experimental program. Since particulate radiation damage cannot be calculated for the wide variety of materials under consideration, reliable experimental data are needed to determine the significance of this type of testing for application in the design of advanced test facilities. Such information is also important to the formulation of a mathematical model to describe this type of damage.

5.2 ACCELERATED TESTING

In laboratory tests, the test article should ideally be irradiated with the anticipated radiation flux for the duration of the mission in question. For the case of extremely long missions where this is not at all practical or possible, it would be desirable to develop some technique of accelerated testing and/or extrapolation methods. It is not as yet clear if or how this can be done. One way of reducing the amount of test time is by increasing the particulate radiation flux rate above what it would be in space. Particulate radiation generators have this capability. Before this technique is applied to general testing, carefully controlled experiments on the effect of particle flux rate on damage must be conducted in order to determine over what limits the flux rate may be increased for the various classes of materials. Some investigators have employed various flux rates while holding the total integrated radiation flux constant and believe this to be a minimum requirement.

There is not much information available on this effect, and not all of the data agree. For example, the work of Pinson (Ref. 40) on the thermal control coating indicates no effect on damage when the flux rate is varied by two orders of magnitude (10^{10} to 10^{12} protons/cm^2/sec) in accumulating a constant total flux. Miller and Campbell (Ref. 39) in a similar experiment on thermal control coatings varied the flux rate also by two orders of magnitude (10^{10} to 10^{12} protons/cm^2/sec). This data indicated a dependence on flux rate. Pinson, Miller, and Campbell included experiments on titanium dioxide; however, it is quite possible that the binder was different in each case.

5.3 IN SITU DAMAGE MEASUREMENTS

Farnsworth (Ref. 37) points out that serious discrepancies can occur in the measured damage of materials unless the measurements are made in situ without a change in the test environment. Since most synergistic measurements have not been of the in situ type, the validity of much of this data is in question. Evaluation of the need for in situ measurements is essential in planning future tests.

5.4 EFFECT OF IRRADIATION TECHNIQUE

In space, the particulate radiation spectrum consists of a varying particle energy and flux rate, and simulation of this spectrum is beyond the state-of-the-art (see Section IV). In ground tests this spectrum must be approximated by applying radiation to the test article in the form of a series of monoenergetic beams or by some irradiation technique to be developed (Ref. 41). At the present, it is believed that simultaneous application of monoenergetic beams will probably provide valid test results, whereas sequential application would lead to more questionable results. However, these technique should be investigated in the laboratory to assure that any deviation that may be introduced by the method of irradiation is well within the limits required for engineering application.

5.5 MOLECULAR TEST POPULATION

The first problem in the production of a molecular test population is the elimination of unwanted molecular contaminants that come from the test chamber. These contaminants produce radiation damage that would not normally be present. Gamble et al. (Ref. 42) have emphasized the difficulties caused by test chamber contaminants, and have shown that careful design of the test chamber and vacuum pumping equipment can reduce the contamination to an acceptable level.

The generation of the desired molecular constituents that exist in a planet's atmosphere can be a problem (Section IV). Near earth, the molecular population consists of helium, molecular oxygen, and nitrogen, and atomic oxygen, nitrogen, and hydrogen. Methods of generating and controlling such an environment should be attempted on a laboratory scale so that the possibility of interaction between these constituents, particulate radiation, and the spacecraft can be investigated. Undoubtedly, similar problems will exist near some of the other planets.

SECTION VI
PROBLEMS FOR INVESTIGATION

Sections IV and V outline the problems which must be solved and the work needed to develop the necessary testing techniques and to lay the foundation for future particulate radiation testing. Once the importance of combined environmental effects has been clearly defined and proper testing techniques have been developed, development testing of full-scale spacecraft and/or subsystems could proceed in the following areas, for example:

1. Determination of the career dose of particulate radiation for an astronaut and of the shielding systems required to limit the astronaut to this level of radiation damage,
2. The interaction of particulate radiation and the astronaut life support systems, and
3. The effect of particulate radiation on vehicle operating systems exclusive of the life support systems.

6.1 SHIELDING SYSTEM

The problem of shielding the astronauts in flight, in planet excursion vehicles, and in planet living quarters will become increasingly acute as longer and longer duration missions are planned because the weight of the shielding systems will increase with time spent in space (Ref. 43). The weight of these systems will be minimized so that a larger percent of the total payload can be devoted to other systems. Consequently, the margin for error in the shielding system will be small, and there will be a greater need to know accurately the performance of these systems. The shielding systems under consideration are solid, magnetic, electrostatic, or some combination of these types. Testing will be required to determine the distribution of primary and secondary radiation throughout the crew areas. Future shielding and testing requirements may be complicated by the presence of on-board nuclear power sources, and in the case of military vehicles, the intense radiation associated with nuclear weapons. Future test facilities should have the capability of investigation of these problems.

6.2 LIFE SUPPORT SYSTEMS

The life support systems define and maintain the environment that will support man or other forms of life in a prolonged stay in space.

As in radiation shielding, short duration flight will not prove to be too critical. However, on long space flights, even the smallest toxic condition may prove to be severe enough to eventually impair the operating efficiency of the crew or produce death. The possibility of poisoning these systems by the interaction between the constituents of the system and particulate radiation makes it highly desirable to conduct ground tests in this area.

6.3 SPACECRAFT OPERATING SYSTEMS

The interaction between the particulate radiation and the spacecraft operating system results in a performance change or failure as a consequence of a change in the properties of the materials in the components. A typical example of this would be the loss of the thermal control of the vehicle because of the deterioration of the thermal control surfaces. Computers, vacuum seals, fuel, solar cells, mechanical and fluid systems, and electronics are but a few of the items that can be adversely affected by overexposure to radiation. Early material studies have been concentrated on improving components that have been found to be radiation sensitive on short missions; however, components that undergo small changes on short missions are potential sources of trouble on longer missions. This problem undoubtedly will require a refinement in the testing of materials and systems for the longer missions.

SECTION VII
CONCLUDING REMARKS

Manned flight capability has been demonstrated in near-earth orbits, and successful, unmanned, deep-space probes have been launched. Plans are underway for the second generation space missions, which, of course, will include manned flights and landings on the planets. Efficient and safe completion of these missions will require more reliable ground test support. Although our knowledge of particulate radiation in space is still continually increasing, sufficient information is now available for the development of the ground test chambers needed to support the deep-space missions of months or years duration. Research and development activity should be concentrated on the following problems:

1. Synergistic testing
2. Irradiation techniques
3. Accelerated testing
4. Molecular background in particulate radiation testing
5. In situ damage measurements

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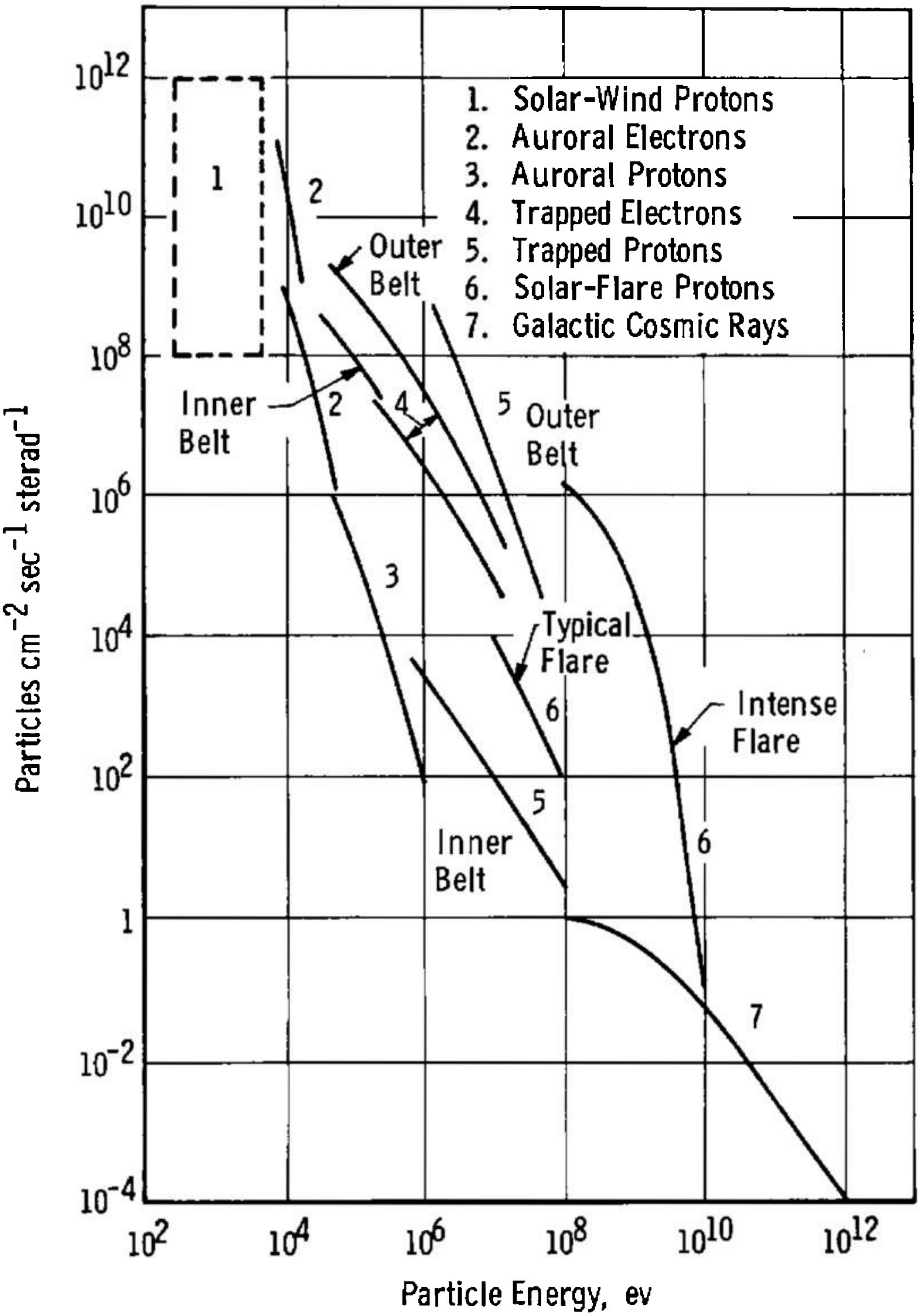

Fig. 1 Space-Radiation Summary (Ref. 2)

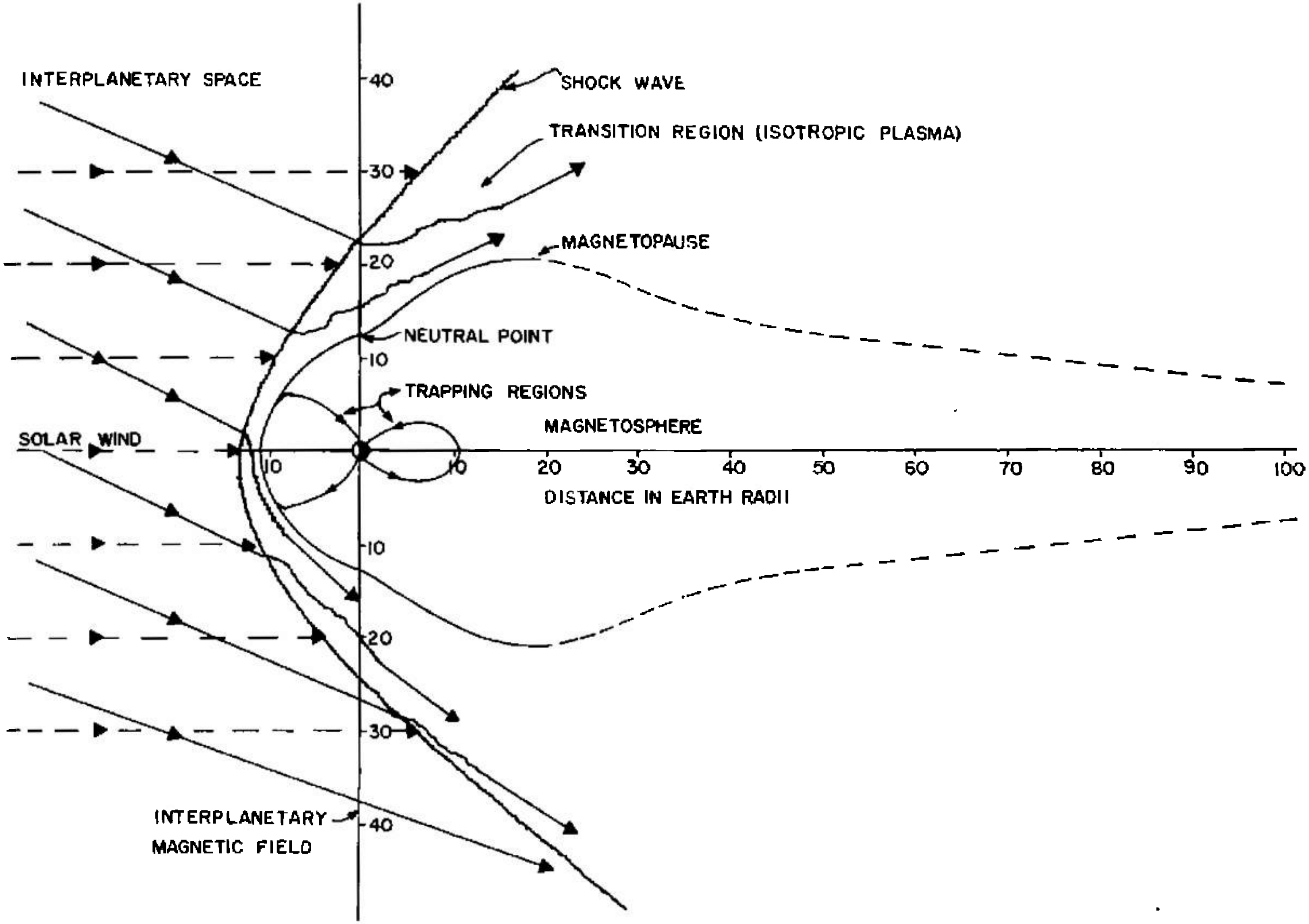

Fig. 2 The Magnetosphere

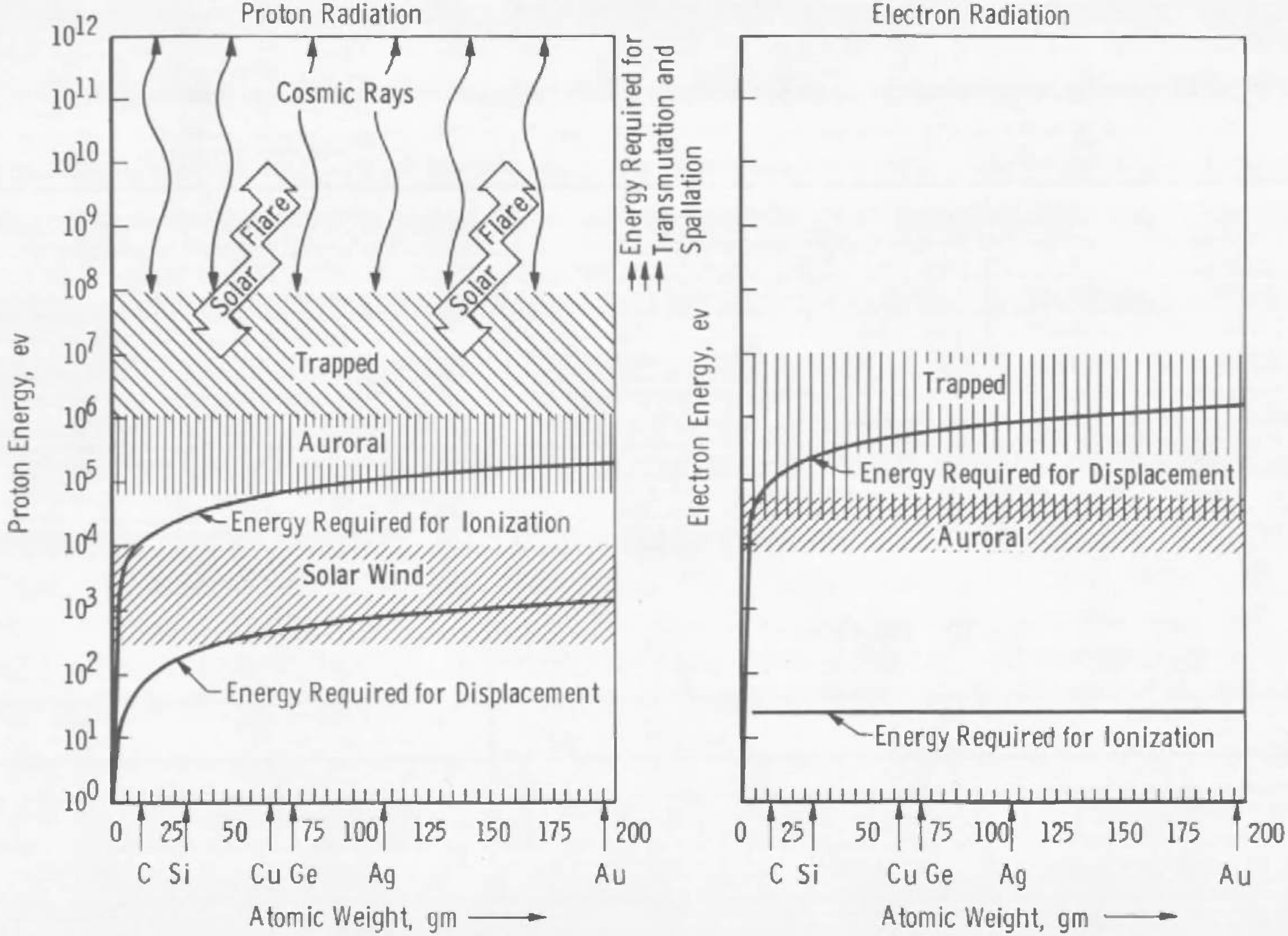

Fig. 3 Displacement and Ionization Threshold for Protons and Electrons

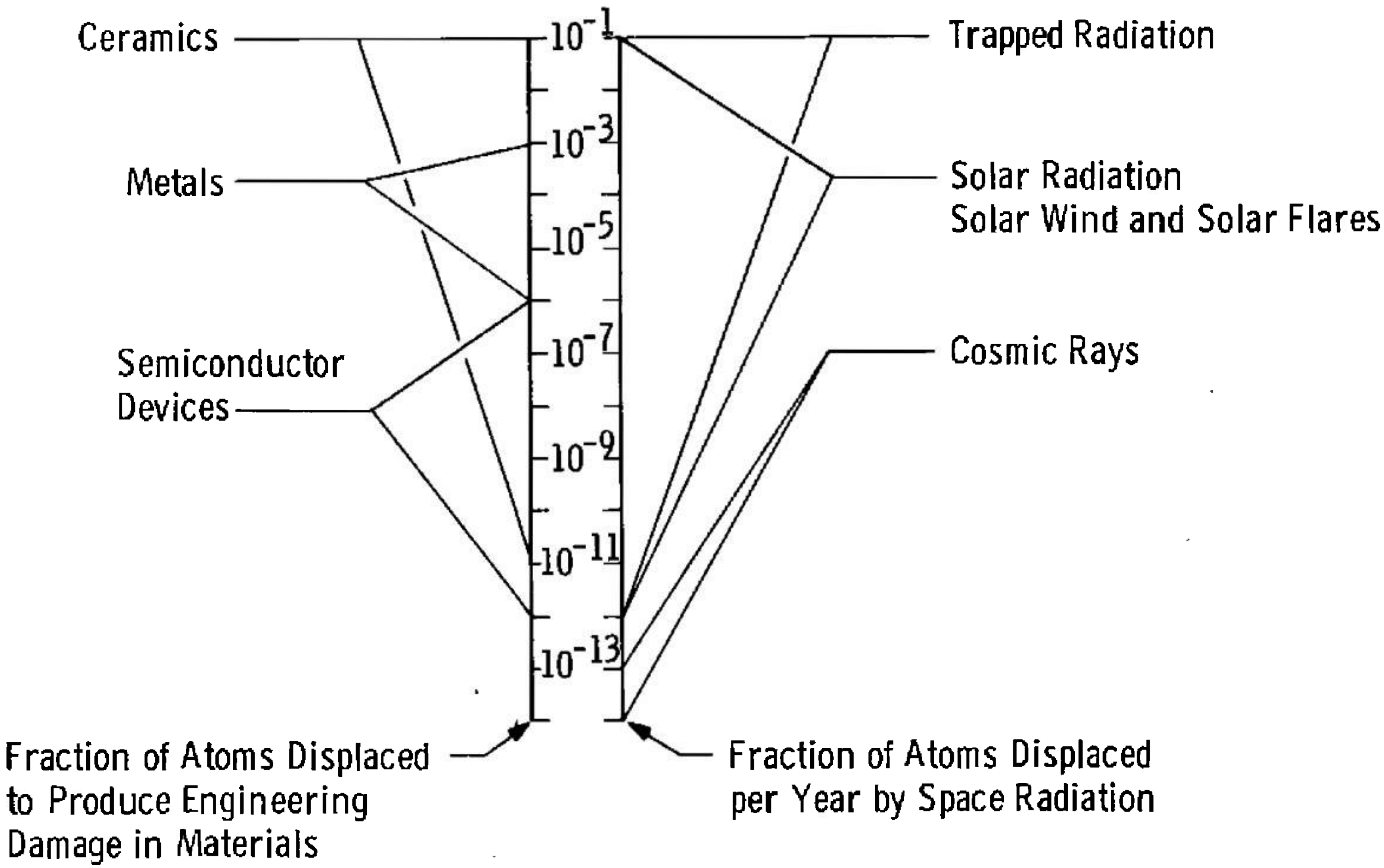

Fig. 4 Comparison of Displacements Produced by Space Radiation and the Displacement Damage Threshold for Engineering Materials

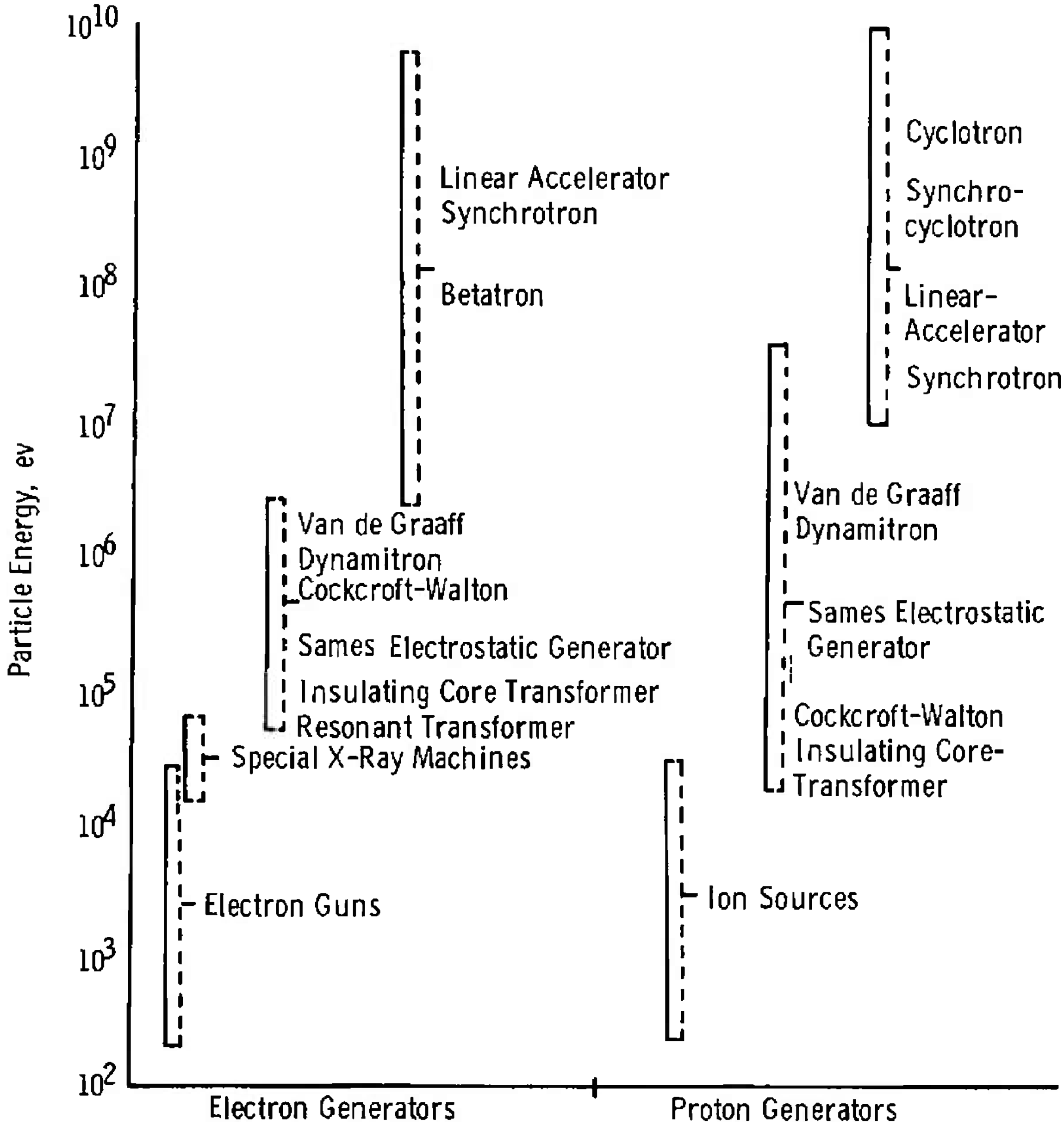

Fig. 5 Particle Generators

TABLE I
SUMMARY OF SOLAR FLARES

Year	Number of events	Solar Proton Integrated Intensity, protons/cm^2	
		> 30 Mev	> 100 Mev
1956	2	8×10^9	8×10^8
1957	4 or 5	4×10^8	1.5×10^7
1958	6	1×10^9	1.4×10^7
1959	4	7×10^9	5.2×10^8
1960	8	5×10^9	4.1×10^8
1961	5	2.7×10^8	3.3×10^7

TABLE II
DISPLACEMENT DAMAGE SUMMARY

Charged Particle	Proton	Electron
Displacement Threshold Range	10 30 ev	10 30 ev
Charged Particle Energy Required for Displacement	(7A) ev	(8000 A) ev
Energy Range for Displacement in the Elements	50 1700 ev (From lithium to uranium)	5.6×10^4 1.9×10^6 ev
Potential Space Radiation Damage Region	All Regions	All trapped electrons; some auroral electrons

TABLE III
PRELIMINARY PARTICLE EQUIVALENCES FOR DAMAGE IN SILICON TRANSISTORS AND DIODES (Ref. 10)

Particle	Number/cm^2
10-Mev Protons	1
Moderated-Reactor Spectrum Neutrons	4
5-Mev electrons	300
Cobalt-60 Gamma Rays	4000

TABLE IV
COMPARISON OF ACTUAL AND ESTIMATED TIMES FOR RADIATION DAMAGE TO OCCUR

Material	Total Flux	Particle Energy, ev	Damage	Radiation Region	Time, yr	Time From Fig. 4, yr	
						Maximum	Minimum
Vylar*	1.7×10^{15} electrons	1.2×10^{6}	59-percent loss of transmission	Trapped	3 - 30	10^{-10}	10^{11}
P/N Solar Cell**	3×10^{13} electrons	1.0×10^{6}	25-percent loss in efficiency	Trapped	0.016	10^{-11}	10^{6}
P/N Solar Cell**	2×10^{9} protons	1.0×10^{6}	25-percent loss in efficiency	Trapped	10^{-7} - 10^{-2}	10^{-11}	10^{6}
Television Camera Lens***	3.6×10^{12} electrons	1.0×10^{6}	Transmission reduced 47 percent	Trapped	0.022	10^{-11}	10^{-10} - 10^{11}

*Ref. 10

**Ref. 18

***Ref. 19

TABLE V
SUMMARY OF RADIATION DAMAGE POTENTIAL

Radiation Region	Displacement	Ionization	Nuclear Interaction
Solar Wind	Yes	No	No
Auroral Radiation	Yes	Yes	No
Trapped Radiation	Yes	Yes	No
Solar Flares	Yes	Yes	Yes
Cosmic Rays	No	No	No

TABLE VI
ERROR IN EQUILIBRIUM SURFACE TEMPERATURE OF A SPHERICAL MODEL BECAUSE OF REFLECTION AND RADIATION FROM A SPHERICAL TEST CHAMBER (Ref. 27)

Model Temperature	200°K	300°K
Ratio of Chamber Diameter to Model Diameter	2.0	2.0
Chamber Wall Temperature	80°K	80°K
Emissivity of Chamber Wall	0.94	0.94
Emissivity of Aluminum	0.47	0.47
Emissivity of White Paint	0.36	0.36
Percent Error Temperature for Model with White Paint Surface	1.2	1.6
Percent Error Temperature for Model with Aluminum Surface	0.9	0.4

TABLE VII
CHEMICAL BOND DISSOCIATION ENERGY OF MOLECULES (Ref. 31)

Molecule	Type of Molecule	Bond Dissociation Energy, ev
MgO	Diatomic	4
SiO	"	8.4
AlO	"	6.0
$MgCl_2$	Triatomic	5.9
NO_2	"	3.1
C-C in C_2H_6	Organic	3.6
C≡C in C_2H_2	"	10

TABLE VIII
STATUS OF GROUND SIMULATION

Simulation Parameter	Status
1. Particulate Radiation	Exact simulation not possible at present time
a. Particle Energy	Monoenergetic test beams are available; energy spectrum simulation not possible
b. Particle Flux Rate	Flux rate simulation possible for monoenergetic test beam
c. Particle Energy and Flux Rate	Simulation not possible at present time. Investigations should be made to determine if this parameter is essential for reliable ground testing.
2. Other Space Parameters	Complete simulation of these parameters not possible at the present time. Need for these parameters during particulate radiation testing should be established.
a. Space Heat Sink	This parameter can be simulated reasonably well.
b. Solar and Thermal Radiation	Exact simulation not possible with respect to necessity of spectral matching
c. Vacuum and Molecular Population	Extremely difficult to produce exact simulation need for these parameters should be established.

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13 ABSTRACT

Space particulate radiation is reviewed, the damage mechanisms are discussed, and estimates are made of the hazardous nature of the various radiation zones. The existing capability for reproducing the space environment in ground test facilities is evaluated. It is concluded that the duplication of the complete space environment is not possible but that useful testing can be accomplished with existing techniques. Research programs are proposed for the evaluation of ground test requirements.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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