

RADIATION EFFECTS ON MATERIALS IN SPACE

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Introduction

Both manned and unmanned vehicles will be needed for Air Force missions in space. This paper sketches the radiation effects situation to be expected. The treatment is general and qualitative with no effort to present detailed, quantitative data.

There are two types of radiation to consider: man made radiation due to reactors, and natural radiations in space. These will be discussed separately here, though in the area of personnel shielding at least, they should probably be treated together.

Reactor Radiations

Currently, solar cells and chemical batteries provide all the auxiliary power used by space vehicles. Their limitations are well known. (1) Batteries suffer from limited life unless recharged by devices like solar cells. Solar cells have a low power output that diminishes as the vehicle recedes from the sun. The SNAP (System for Nuclear Auxiliary Power) program of the AEC is set up to overcome these limitations by using radioisotopes and nuclear reactors to generate auxiliary power. Odd-numbered SNAP's use the heat from radioisotopes to generate electricity; even-numbered SNAP's use nuclear reactors as energy sources. These two types of energy source supplement each other. Radioactive isotopes may be used up to a few thousand watts, while nuclear reactors may be used from there on up into the megawatt range (1,2). This paper is not concerned with the design problems of SNAP generators but rather with their leakage radiation and its effect on materials.

Sufficient shield weight can reduce the leakage radiation to any value desired; however, because of the weight penalty the design leakage radiation will have to be as large as can be tolerated to save shield weight. Since the leakage radiation in unmanned vehicles will be determined by the radiation tolerance of its materials and components, these will have to be designed for maximum radiation resistance.

As an example of the leakage radiation to expect from an isotope powered SNAP, consider the SNAP 1A (3). This unit is designed to furnish 125 watts of electrical power for about one year. It is fueled with 8.8×10^8 curies of radioactive cerium with a 285 day half life, and its weight is about two hundred pounds. Radioactive cerium decays by beta emission which is easy to shield. However, there is also considerable gamma ray emission associated with the cerium and its daughter products. Accordingly, SNAP 1A is shielded for ground handling by four thousand pounds of mercury which reduces the leakage radiation at three feet to less than one tenth roentgen per hour (4). The mercury is drained out before space flight. Without the mercury the resulting dose rate at three feet is expected to be 20,000 roentgens per hour, which over a period of a year results in a total exposure dose of about 10^8 roentgens. Organic materials and solid state electronics are disturbed

by doses this large. There are plans to scale up the power from approximately 100 watts to perhaps twenty kilowatts which could increase the radiation dose rates by a factor of one hundred or so, demanding more severe requirements on materials and components.

SNAP's powered by nuclear reactors are proposed to handle power requirements in the range of one hundred kilowatts and up (2). SNAP 8, for example, is a low power reactor to provide thirty kilowatts of electricity. The leakage radiation through the four hundred pound shadow shield is expected to be a dose rate of about 1000 roentgens per hour of gammas and a fast neutron flux of 30,000 neutrons per cm^2/sec^2 . Again, the allowable leakage radiation in unmanned vehicles will be determined by the radiation tolerances of materials and equipment. There is a lot of radiation effects data available in this connection but it does not apply across the board in the vacuum of space.

Low power SNAP's will probably be used only on unmanned vehicles where the leakage flux will be limited by the radiation sensitivity of materials and components. On the other hand, power SNAP's (one hundred kilowatts and up) have application to manned vehicles also. Man is thousands of times more radiation sensitive than is any inanimate object in a space vehicle and the problem of shielding-weight increases in proportion in a manned vehicle. Interplanetary travel by ion propulsion will require megawatts of power and presumably these missions will eventually be done in manned vehicles. The nuclear rocket (Rover) is talked of in terms of hundreds or even thousands of megawatts. What must be done to shield crew members from these reactor radiations? The fact that the vehicle will be surrounded by a vacuum in outer space rather than by air, which would back scatter the radiation, should simplify the shielding design. Weight savings should result from shadow shields designed to scatter radiation into space instead of relying exclusively on absorption (5). Even so, it appears that considerable shield weight will be needed for personnel in vehicles using high power reactors. The most efficient position for scatter shielding is probably close to the reactor where smaller angle scattering can deflect the radiation from the solid angle subtended by the crew compartment. Nevertheless, if protection from the natural radiations in space is considered at the same time, it may be well to put a disproportionately large fraction of the shield weight at the crew compartment so that if the natural radiations from space build up, the crew can shut down the reactor and retire into the crew compartment part of the divided shield for protection.

Both neutrons and gammas are scattered most efficiently (on a weight basis) by low atomic number materials, particularly hydrogen. Light metal hydrides and organic materials rich in hydrogen are candidate materials for scatter shields.

Another method for shielding in space is $1/R^2$ shielding; simply putting the crew compartment as far as possible from the reactor. This is feasible because stresses due to gravity are much reduced in space so that the power source can be separated by a considerable distance from the equipment it operates and can be connected by relatively long, light conduits.

Natural Space Radiations

The following natural space radiations are considered: galactic cosmic rays, solar cosmic rays, Van Allen radiation belt electrons, and Van Allen radiation belt protons.

Conventional Shielding

Space radiation fluxes are much less than those of nuclear reactors but their effects are less well known. In addition they affect all space missions including those that do not

involve nuclear power (6). Some of the results and conclusions that follow are based on our calculations. The differential spectra used are questionable, particularly the spectrum of the Van Allen radiation belt electrons which is not well known. However, the conclusions are qualitative and are not greatly dependent on the particular spectra chosen.

Cosmic rays have been studied extensively (7). Galactic cosmic rays originate outside the solar system and seem to permeate the vacuum of space. Their composition is quite well known, mostly protons with a smattering of heavier elements. Conventional shielding probably cannot shield the primaries effectively. Fortunately the dose rate expected from them in space is only about 0.001 roentgen per hour (6) which could be considered negligible except for uncertainty about the biological effects of the high atomic number component of the radiation. Galactic cosmic rays will not be considered further here.

Solar cosmic rays are bursts of high energy protons associated with flares on the surface of the sun. These bursts last a few hours, decaying as the square of the time. Solar cosmic ray bursts are classified as high energy events or low energy events. Their occurrence is unpredictable.

Low energy solar cosmic ray bursts average about one a month during the active part of the eleven year solar cycle, and are less frequent during the solar minimum. They contain protons up to several hundred mev energy. A rather intense low energy cosmic ray burst occurred on 12 May 1959. Its spectrum was measured at balloon altitude (8). Proton range and energy loss data can be used with this spectrum to compute the dose to be expected. Using Sternheimer's data (9), our calculations indicate a dose of about 27 rad through $1\frac{1}{2}$ inches of aluminum (10 g/cm^2 of absorber). This small a dose would have a negligible effect on materials and could be tolerated by man. The proton spectrum is steep, making it relatively easy to shield. Nine inches of aluminum (20 g/cm^2 of absorber) would reduce the dose to 1.5 rad. Accordingly, it appears that conventional shielding can reduce to tolerable levels the radiation dose due to solar cosmic rays from low energy events.

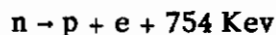
This may also be true of solar cosmic rays from high energy events. Nevertheless, these constitute a major radiation hazard to man in space. There have been half a dozen or so high energy events since 1940 which contained protons with energies of tens of billions of electron volts. A particularly intense high energy event took place on 23 Feb 1956. We did not actually compute doses expected from this event; however, reference (6), shows 40 times as many protons able to penetrate $1\frac{1}{2}$ inches of aluminum as there were in the event of 12 May 1959. Hence, the dose should be about forty times as great or about 1000 rad. This would not significantly effect materials but would be fatal to personnel. Reference (6), also shows that about 100 times as many protons are able to penetrate 9 inches of aluminum, as there were in the event of 12 May 1959, which implies a dose of about 150 rad through a 3-inch thickness of shielding. A dose of 150 rad would not be fatal and the risk of a 100 rad dose could probably be tolerated since high energy events are so infrequent. Unfortunately, future high energy events can be expected to exceed in intensity that of 23 Feb 1956. Another disturbing feature of these events is the large flux of protons with energies above one billion electron volts. It would require five feet of structure to shield 1 Bev protons by conventional means. For this reason unconventional shielding techniques appear attractive. Furthermore the biological effects of high energy protons are not known but are probably worse than the dose in rads implies. This is also true, to a lesser extent, of their effects on materials in general.

Girdling the earth are two regions of trapped radiation called the Van Allen radiation belts (10). The inner Van Allen belt contains trapped protons and electrons; the outer Van

Allen belt primarily trapped electrons. The heart of the inner zone is about 2000 miles from the earth at the equator; the heart of the outer zone, about 10,000 miles. This paper will not discuss the shape or extent of these zones which is covered in a number of survey articles (11). Suffice it that these regions are bounded, and can either be traversed quickly or avoided altogether in some missions. There may be other missions where a vehicle must spend considerable time within them.

Treatment of the trapped protons is similar to the previous treatment of low energy solar flares except that dose rates are significant instead of total doses since the flux of trapped protons appears to be quite stable, and doesn't decay with time as does the proton flux from solar flares. The trapped protons have energies up to several hundred Mev as do the protons from low energy solar flares. However, the spectrum (12) of trapped protons is much flatter which makes it much more difficult to shield by conventional means. Our calculations show a dose rate of about 4 rad/hr through $1\frac{1}{2}$ inches of aluminum (which is comparable to the maximum dose rate from the 12 May 1959 solar flare of 27 rad/hr). However, 3 inches of aluminum, which would reduce the flare to 1.5 rad/hr, reduce the trapped protons only to 2.2 rad/hr. Again these dose rates pose minor problems for most materials but are much too high for people to loiter in.

The Van Allen Radiation belts also contain trapped electrons. One mechanism for their production is by the decay of neutrons which are generated by cosmic rays interacting with the atmosphere (13). The neutron decay is as follows:



This implies that electrons are injected into the radiation belts with energies of 754 Kev or less. The fluxes of electrons in the Van Allen belts are not yet as well known as the proton fluxes but the electron fluxes appear to have an effective upper limit of around 800 Kev. These electrons can be completely stopped by a few millimeters of aluminum and will not penetrate normal satellite structure to effect directly materials or personnel. However, when electrons are stopped, bremsstrahlung are produced and the effects of these must be considered. Bremsstrahlung production varies directly with the atomic number of the material that stops the electrons. Calculations for electrons stopped in aluminum indicate dose rates of a couple rad per hour of rather soft x-rays. One tenth inch of lead can reduce this dose rate by a factor of one thousand to completely tolerable values. Bremsstrahlung production can be reduced by stopping the electrons in material of lower atomic number. Special low atomic number coatings may be worth developing if it turns out that other planets have trapped electron belts a great deal more intense than that of the earth.

Unconventional Shielding of Protons

Conventional shielding is based on protons losing energy by ionization and excitation processes. This is a reasonable way to shield against 100 Mev protons which are stopped by $1\frac{1}{2}$ inches of aluminum. There may be better ways to reduce the hazards of Bev solar flare protons which have ranges of several feet in aluminum. In addition, protons over a few hundred Mev can create unexpected and exotic secondaries, like mesons in conventional shields (1). Even low energy protons coming through a shield are a source of concern since their biological effects are not well known.

Magnetic shielding and electrostatic shielding take advantage of the charged nature of the radiation to be shielded. Magnetic shielding relies on a magnetic field of sufficient strength to deflect the protons. To produce such a field with existing technology would

require very large electric currents which are difficult to provide under present weight limitations. In addition, inherent properties of magnetic fields are such that protons coming in at the magnetic poles would be undeflected.

Electrostatic shielding appears more attractive. If a few coulombs of negative charge can be removed from a satellite, it would charge up to some billions of volts. Any proton with energy less than this would not even reach the vehicle. It may be feasible to charge up condensers on the satellite and propel the negative plates out into space until a coulomb or so of negative charge has been disposed of. For example, balloons with metallized surfaces could be pushed out a porthole, inflated, charged up, and propelled into space. Each would carry off a certain amount of charge. Another approach would be to use a hot filament to inject electrons into the earth's magnetic field where they would be trapped and prevented from returning to the vehicle.

Unconventional Shielding of Electrons

Trapped electrons appear to pose no great problems to personnel or materials that can be protected by a reasonable amount of structure. Optical components and solid state devices such as solar cells may have to be located outside the structure for operational reasons and are not so readily shielded. For this reason, magnetic or electrostatic shielding may be worth considering. Magnetic shielding has the advantage of being effective for both electrons and protons, while electrostatic shielding could be used for unmanned vehicles in the outer Van Allen belt where protons would not be bothersome.

Effects of Natural Space Radiation on Materials

There is presently considerable data available on the effects of electrons on materials. A great deal of x-ray and gamma ray data is also applicable since secondary electrons are produced by the interaction of high energy photons with matter. In general, the electron's charge is responsible for its interactions with materials. Electrons lose energy by producing ionization and excitation of the orbital electrons of the constituent atoms and molecules. The observed radiation effects are then largely due to the subsequent behavior of the ionized and excited molecules.

Protons are singly charged also and produce ionization and excitation in a manner exactly analogous to electrons. * A priori, the ionization and excitation effects of a proton will be identical to the effects of an electron that deposits energy in the sample at the same rate, i.e., same linear energy transfer or stopping power or $\frac{dE}{dx}$. However, additional interactions occur with protons, particularly protons over a few hundred Mev.

Protons that stop in material, lead to interstitial hydrogen. The effects of this, using actual spectra have not been evaluated. Protons are also capable of nuclear interactions with cross sections measured in millibarns (14,15). These reactions are unlikely compared to ionization and excitation with cross sections equivalent to millions of barns. However, the ranges of high energy protons are so long that a sizeable fraction of the protons, perhaps as many as 1/10 or so, will undergo a nuclear reaction of some sort before being stopped. These reactions include meson production, spallation, and inelastic scattering.

* Incidentally, reporting proton dose in roentgens is a little questionable since roentgens can be stretched to apply to ionization, and protons lose as much or more energy by excitation than by ionization. Absorbed dose in rad or ergs/gram is much more applicable.

The importance of these reactions has not been assessed with respect to the proper behavior of materials in the high energy radiation environment of space. Additional basic cross section data on these reactions is very desirable, particularly in the high energy proton range.

Further radiation effects discussion will consist of sketching the problems of three arbitrary classes of materials:

- 1) usual engineering materials protected by a reasonable amount of structure
- 2) materials which are not normally shielded by structure
- 3) biological materials (man)

No serious problems appear in engineering materials protected by a reasonable amount of structure. Trapped electrons are completely shielded and the resulting bremsstrahlung are negligible. Such materials should be quite unaffected by proton doses of a few hundred rad from solar cosmic rays and proton dose rates of a few tens of rad per hour from trapped protons.

Solar cells, and optical components may have to be located on the outside of the vehicle structure to function properly. Our calculations show dose rates up to 10^8 rad/hr of unshielded electrons in the trapped radiation belts. There is some data on the effects of electron doses on solar cells (16). There appears to be significant damage at 10^7 rad of 300 Kev electrons so some provision must be made for shielding such devices. Glass plates have been used but radiation induces color centers in transparent materials cutting down their light transmission. Optical shielding is needed that does not lose its transparency. This might be accomplished by permitting the thin region affected to flake off exposing a new surface or by incorporating a provision for annealing out the color centers possibly by heat from the sun. It may be necessary to shield sensitive components by burying them in the structure of the vehicle and conducting light or infrared to them by front surface mirrors which would not be affected by the intense radiations in space.

Biological materials are the most sensitive materials which must be shielded from the natural radiations in space. Accordingly, shielding materials and configurations must be evaluated on the basis of how well they shield materials, and configurations must be evaluated on the basis of how well they shield people. The greatest uncertainty appears to be the biological effects of protons. At the high energy end of the spectrum, spallation and meson production in tissue must be evaluated. At the low energy end, the mechanisms of energy deposition do not appear to be too well known and should be better defined. All these effects are lumped into a parameter called the relative biological efficiency (RBE). The tissue dose in rads (due to ionization and excitation) must be multiplied by an RBE for the spectrum in order to get a number related to actual biological tolerances.

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Contrails