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RADIATION HAZARDS ON SPACE MISSIONS OUTSIDE THE MAGNETOSPHERE

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ABSTRACT

Future space missions outside the magnetosphere will subject astronauts to a hostile and unfamiliar radiation environment. An annual dose equivalent to the blood-forming organs (BFOs) of ~0.5 Sv is expected, mostly from heavy ions in the galactic cosmic radiation. On long-duration missions, an anomalously-large solar energetic particle event may occur. Such an event can expose astronauts to up to ~25 Gy (skin dose) and up to ~2 Sv (BFO dose) with no shielding. The anticipated radiation exposure may necessitate spacecraft design concessions and some restriction of mission activities. In this paper we discuss our model calculations of radiation doses in several exo-magnetospheric environments. Specific radiation shielding strategies are discussed. A new calculation of aluminum equivalents of potential spacecraft shielding materials demonstrates the importance of low-atomic-mass species for protection from galactic cosmic radiation.

INTRODUCTION

Planning for future space missions outside the Earth's magnetosphere has been initiated /1/. The establishment of permanently manned bases on the Moon and exploratory manned missions to Mars are receiving increasing support from policy makers /2/ and citizen groups. These exciting developments have stimulated us to assess the radiation hazards on future missions in order to determine whether the missions are feasible and to recommend strategies for protecting the astronauts from adverse effects.

Proposed missions outside the magnetosphere will thrust astronauts into a hostile and unfamiliar space radiation environment. The environment consists of highly-penetrating galactic cosmic radiation (GCR) with occasional activity from solar particle events (SPEs). Astronauts in the 28.5° inclination Space Shuttle orbits have received no significant exposure from either of these radiation components. The Earth's magnetic field forms an effective shield which deflects most charged particles from equatorial regions.

The proposed missions require significantly longer periods outside the magnetosphere than previous missions. For example, a round trip flight to Mars requires approximately 2 years plus additional time for exploration in orbit around and on the surface of Mars. This may be compared with about 2 weeks for lunar explorations during the Apollo era. The expected doses, and hence the consequences of these exposures, are dramatically increased by the longer duration.

Galactic cosmic radiation consists of protons and heavy ions with energies per nucleon in the range 100 MeV to 10 GeV. These particles have been observed on space flights outside the magnetosphere with plastic-track detectors /3/ and as light flashes in the astronaut's eyes /4/. Astronauts have never been subjected to long-term (≥ 1 year) exposure from GCR heavy ions. The assessment of radiation effects from heavy ions is difficult because there are no human epidemiological data available from terrestrial sources.

Solar energetic particle events are a more familiar concern on missions outside the magnetosphere. However, with the advent of long-duration missions, an anomalously-large SPE may occur with a probability of 25% to 50% /5/ (a three-year mission has been assumed). We feel that an anomalously-large SPE should be considered a "likely event" rather than a "remote possibility" by mission planners. In assessing the risks from such an event we have used the August, 1972 event as a model because it is the best-measured and most-intense SPE known. Use of other models leads to significantly different risk assessments.

TRANSPORT MODEL

The radiation dose calculations presented here were performed using the transport code, UPROP /6/, and the most recent CREME GCR environment model /7/. The codes provide a prediction of the fluxes, LET spectra, and radiation doses from cosmic-ray heavy ions ($1 \leq Z \leq 28$) over energies per nucleon in the range 1 MeV $\leq E \leq$ 100 GeV. Calculations are performed on a 500 point logarithmically-spaced energy grid.

The transport code provides an exact numerical solution of the one-dimensional continuity equation taking into account both ionization losses and nuclear fragments. Ionization losses are treated in the continuous slowing down approximation. Nuclear fragmentation processes are treated in the straight-ahead approximation which assumes that fragments maintain the same velocity as their progenitors after a nuclear interaction. All orders of fragments (secondaries, tertiaries, etc.) are followed in the calculation.

The UPROP code has been validated by comparison with two other transport codes which were written independently and use different numerical methods. The first of these codes /8/ does not follow nuclear fragments and uses different fragmentation mean free paths and ionization loss rates from UPROP. The computed radiation dose from GCR at solar minimum behind 1 g cm^{-2} aluminum shielding using these two codes agrees to within 3%. The dose equivalents (using conventional quality factors /13/) agree to within 4%.

The second code /9/ uses numerical derivatives to solve the transport equation. It has been applied to GCR transport in an early calculation by our group /10/. Using the code UPROP we have repeated that calculation taking into account differences in quality factor and environmental model from our present procedure. At the center of a 5 g cm^{-2} spherical shell of water we compute an annual dose of 9.1 rad and dose equivalent of 30.2 rem, to be compared with 9.2 rad and 31 rem in /10/ indicating excellent agreement between codes.

It is of interest to note that our present calculations of these quantities are 11.6 rad and 48.6 rem, respectively. The doses have increased as a result of changes in quality factor and environment model. Most of the difference is attributed to the most recent update of the CREME GCR model /7/. The dose equivalent is 12.5% greater when the approximate quality factors of /10/ are replaced with a precise representation of the conventional quality factor /13/.

The CREME GCR environmental model has been compared with spaceflight dosimetry data from Apollo and Skylab missions /11/. Model LET spectra were within a factor of 2 or 3 of measured LET spectra. A number of factors were not treated fully in that comparison, including actual shielding distributions around the dosimeters and the limitations of plastic-track detector response. Work is currently underway to explore these factors.

RADIATION ASSESSMENT METHODOLOGY

In this paper, estimates of the risk from ionizing particle radiation are performed using conventional radiation protection practice. The dose in water is obtained from an LET (linear energy transfer) spectrum computed by the transport code and is used as an estimate of the tissue dose. The dose equivalent /12/ is obtained using the quality factors recommended by the ICRP (International Commission on Radiological Protection) /13/. Dose is thought to be better correlated with acute radiation effects; dose equivalent is thought to be better correlated with long-term, stochastic effects. Other approaches to space radiation protection may be useful; one such approach based on particle fluences is considered in an accompanying paper /14/.

Two methodologies for evaluating the risks of a given radiation exposure are used here. The first, and most fundamental, is to assess the risk that radiation exposure will endanger the completion of a mission by disabling the astronauts. The second is to verify that radiation dose equivalents are within legislated limits and as low as reasonably achievable.

Acute exposure to radiation from an intense solar particle event may affect astronaut health during a space mission. Potential short-term health problems of space radiation exposure have been addressed by a panel of the National Academy of Sciences and National Research Council /15/. They established effective dose (ED) thresholds for erythema (ED_{10} = 4 Gy, ED_{50} = 5.75 Gy), prodromal sequelae (ED_{10} = 0.4-0.9 Gy, ED_{50} = 1.0-2.4 Gy), and hematological depression (ED_{10} = 0.5-0.8 Gy, ED_{50} = 1.2-1.9 Gy). Each of these effects is manifested within a week or two of exposure. The impact of these health effects on the crew depends on the number of astronauts affected and the degree of discomfort or incapacitation. The panel states that death from radiation, 2 to 8 weeks after exposure, occurs with LD_{10} = 2.2 Gy and LD_{50} = 2.85 Gy. With medical care, an astronaut might survive greater exposures. The dose-response relationships determined in /15/ are subject to change as new data become available.

Cancer mortality is the guiding factor in NASA radiation protection guidelines. These guidelines are currently under study by a committee of the NCRP (U.S. National Commission on Radiation Protection and Measurement) /16/. The Committee has recommended monthly, annual and career dose limits to the skin, eye lens, and bone marrow for male and female astronauts. Career limits for the bone marrow are based on a 3% lifetime excess risk of *death* from cancer. Monthly and annual limits for the bone marrow are 0.25 Sv and 0.5 Sv.

The NCRP radiation guidelines were designed specifically for application on the Space Station. It is not yet clear whether these guidelines will become a *de facto* standard for all spaceflights. Furthermore, the guidelines are subject to change as new data, for example the reassessment of doses to A-bomb survivors /17/, become available.

It is noteworthy that the NCRP annual limit of 0.5 Sv to the BFOs is 10 times greater than the maximum allowance for terrestrial radiation workers and 100 times greater than allowed for the general population. Typical whole body exposure from natural background radiation in the U.S. is ~0.001 Sv yr^{-1} /18/. The career limit recommended by the NCRP is 4.0 Sv which may be compared with a career limit of 2.35 Sv for terrestrial radiation workers.

RADIATION RISKS

The dose equivalent as a function of aluminum shielding depth has been calculated and is shown in Figure 1. The dose equivalent has been evaluated at zero tissue depth (skin dose). The maximum skin dose equivalent from GCR at solar minimum is about 0.75 Sv yr^{-1} for shielding of 1 g cm^{-2}. For thinner shielding the GCR model is uncertain because of great variability in the low-energy components. The BFO dose equivalent may be estimated by adding 10 g cm^{-2} to the shielding thickness. The maximum BFO dose equivalent from GCR at solar minimum is about 0.5 Sv yr^{-1}.

Four components of the dose equivalent are shown. The primary protons and heavy ions (i.e., cosmic rays which have not suffered nuclear interactions) constitute most of the dose equivalent for thin shielding. Fragments are reaction products of the GCR which have undergone nuclear interactions. Fragments are a relatively minor constituent of the total dose equivalent. Target secondaries are protons, alpha particles, and heavy recoil nuclei which have been accelerated from rest in the target material by primary cosmic rays and their reaction products. Neutrons with energy < 20 MeV are another target secondary, but have required a different computer code for their estimation /19/. A quality factor of 20 was used for low-energy neutrons.

We note that accurate estimation of the fragment contribution to the total dose requires many nucleus-nucleus cross sections which are unmeasured. It is of interest that the fragment contribution is at most ~10% in our calculations. Relatively large errors in the cross sections can therefore have only a minor effect on the estimate of total dose from GCR. Uncertainties in the radiation environment, biological effects of heavy ions, and dosimetry are of considerable importance.

Figure 2 shows a breakdown of the GCR primary and fragment dose equivalent according to charge. Iron makes up approximately 25% of the dose equivalent. Other important species are silicon, magnesium, neon, oxygen, carbon, helium, and protons. The contribution to dose equivalent is strongly weighted toward the higher-charged cosmic ray species, rather than those which are most abundant. This results from a combination of the Z^2 dependence of LET and a quality factor of up to 20 for heavy ions.

Radiation doses for the August, 1972 anomalously-large SPE are shown in Figure 3. Two calculations have been performed. The first /20/ shows the dose equivalent to the BFOs as a function of aluminum shielding thickness. This computation is useful in evaluating the contribution of the SPE to the monthly BFO limits proposed by the NCRP. The second calculation shows the skin dose as a function of aluminum shielding thickness. This computation is useful for determining the shielding required to prevent early effects of radiation. The reader should note that the BFO dose equivalent and the skin dose in Figure 3 are in different units. The dose equivalent to the BFOs may be useful for predicting leukemia incidence many years after a spaceflight; the skin dose may be useful for predicting immediate skin discomfort or burns which can result from acute radiation exposure.

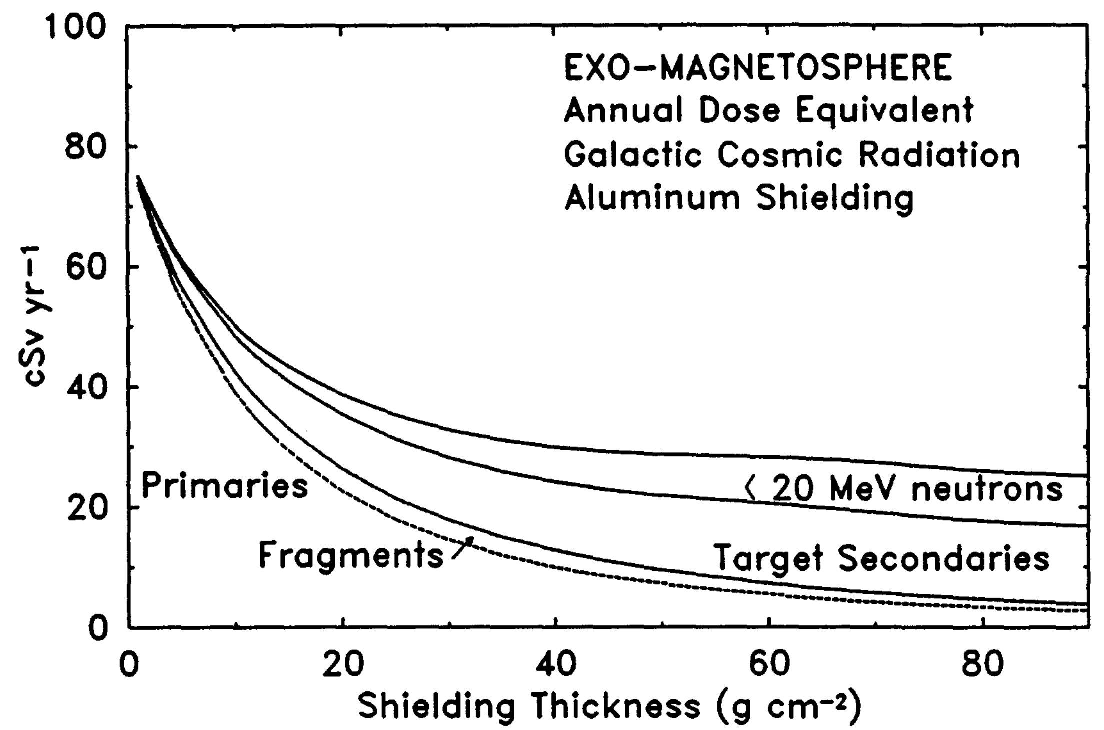

Figure 1: Annual dose equivalent from galactic cosmic radiation at zero tissue depth as a function of aluminum shielding thickness.

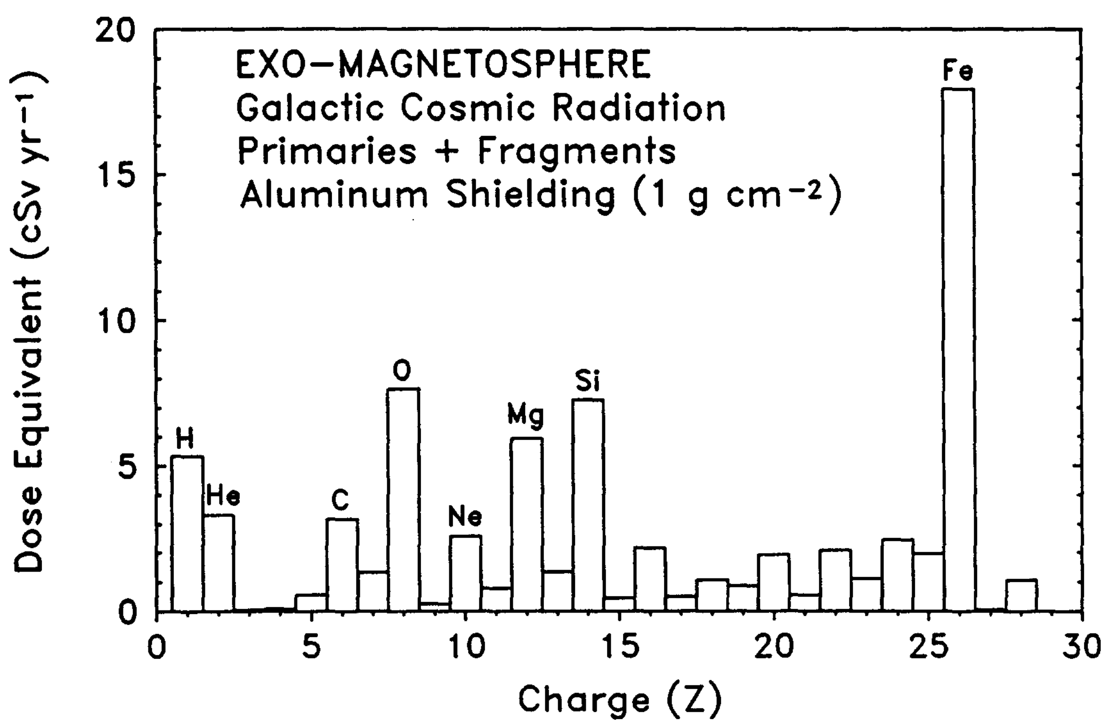

Figure 2: Elemental contributions to the dose equivalent from galactic cosmic radiation at solar minimum after passage through 1 g cm^{-2} of aluminum shielding.

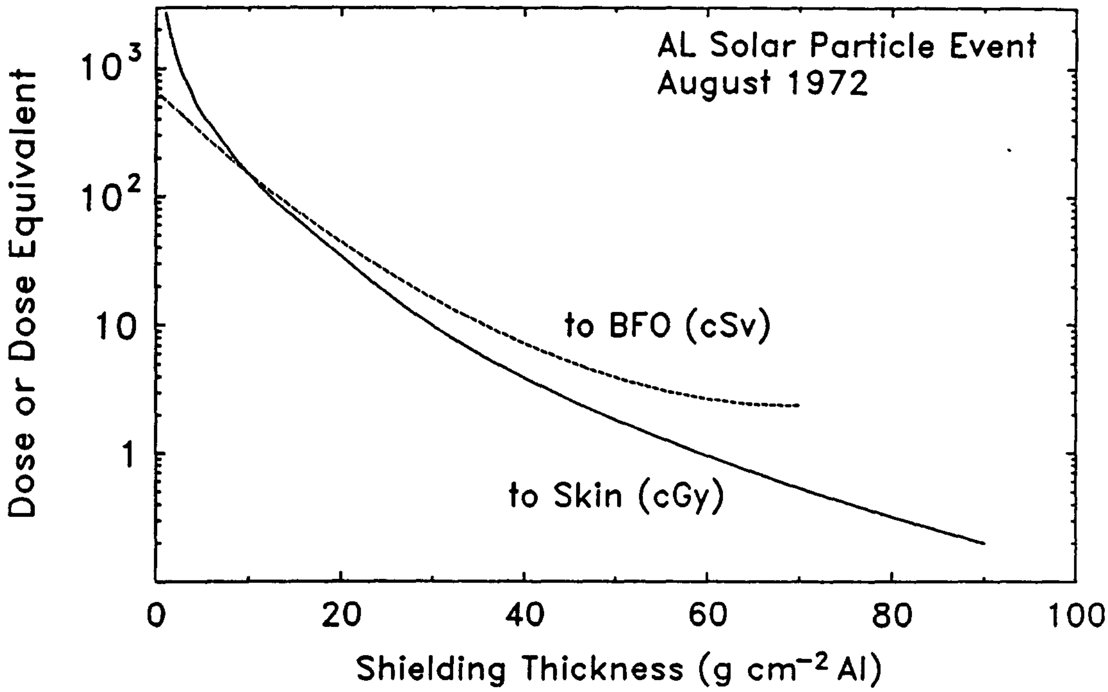

Figure 3: Dose equivalent to the blood-forming organs and skin dose as a function of aluminum shielding thickness for the August, 1972 anomalously-large solar energetic particle event.

SHIELDING CONSIDERATIONS

Requirements for shielding from the anomalously-large SPE may be derived from Figure 3. Early skin effects (erythema) are an important consideration with doses above 4 Gy. This threshold is exceeded when the shielding thickness is < 5 g cm^{-2} for a 4π steradian exposure or < 3 g cm^{-2} for a 2π steradian exposure. When astronauts are shielded by less than these amounts, early skin effects will be a concern.

Other early effects (prodromal sequelae and hematological depression as defined in /15/) occur as a result of whole body irradiations. They are important when doses exceed 0.5 Gy. Figure 3 indicates that 17 g cm^{-2} of shielding reduces the skin dose below this threshold. The body provides self-shielding approximately equal to 10 g cm^{-2} of aluminum, therefore we may conclude that 7 g cm^{-2} of aluminum shielding will protect astronauts from other early effects. With the same assumed body self-shielding, the maximum whole-body dose for the August, 1972 event is ~1.5 Gy, which is below the threshold for lethality, LD_{10}.

Astronauts can be protected from the early effects of an acute exposure to radiation from a SPE with a storm shelter having > 7 g cm^{-2} aluminum shielding or its equivalent over 4π steradians. We feel that such a shelter should be mandatory on all long-duration missions outside the magnetosphere because of the large probability of a SPE. This shelter insures that the mission will not be jeopardized by a SPE of the same magnitude as the August, 1972 event.

Solar particle events also contribute to the monthly, annual and career radiation doses of the astronauts. Astronaut radiation doses are likely to be restricted within legislated limits which may be similar to the NCRP recommendations. In addition, the doses must be minimized in accordance with the ALARA (as low as reasonably achievable) principle. According to Figure 3, a storm shelter providing 25 g cm^{-2} (~9 cm) of aluminum shielding is required to ensure that the monthly dose equivalent to the BFOs does not exceed 0.25 Sv. 19 g cm^{-2} (~7 cm) of aluminum shielding is required if the monthly limit is 0.5 Sv. We point out that such limits can impose extraordinary mass requirements on a long-duration spacecraft.

Requirements for shielding from GCR may be derived from Figure 1 and legislated dose limits which do not exist currently. For purposes of this example we will use the NCRP radiation dose guidelines which restrict the number of excess cancer deaths due to astronaut occupational radiation exposure. With 10 g cm^{-2} of body self-shielding, the annual dose equivalent is about 0.50 Sv. This is exactly the annual limit to the BFOs recommended by the NCRP. No additional shielding is required to fall within the NCRP monthly and annual recommendations. Age- and sex-dependent career limits may restrict the length of a mission or the minimum age or sex of participating crew members.

If mission planners wish to apply a safety factor of 2 to the GCR dose limit to account for the multitude of uncertainties in this dose assessment (which are at least a factor of two), then no practical amount of aluminum shielding can offer enough protection to the astronauts at the level of the NCRP guidelines. In Figure 1, the radiation dose remains above 0.25 Gy to beyond 30 cm of aluminum. Shielding from GCR, if necessary, would be required in all habitable parts of the spacecraft.

Since aluminum shielding is inadequate to provide a significant reduction in the GCR dose, we have investigated the radiation dose from several other shielding materials. Our choices include: (a) copper, about equivalent to iron, another common spacecraft material, (b) water, a requirement for life-support systems, (c) hydrogen, a common spacecraft fuel, (d) lead, a useful material for shielding from gamma rays, and (e) methane, a hydrogen-rich material which may also serve as a fuel. Annual dose equivalent versus shielding thickness for these materials is shown in Figure 4.

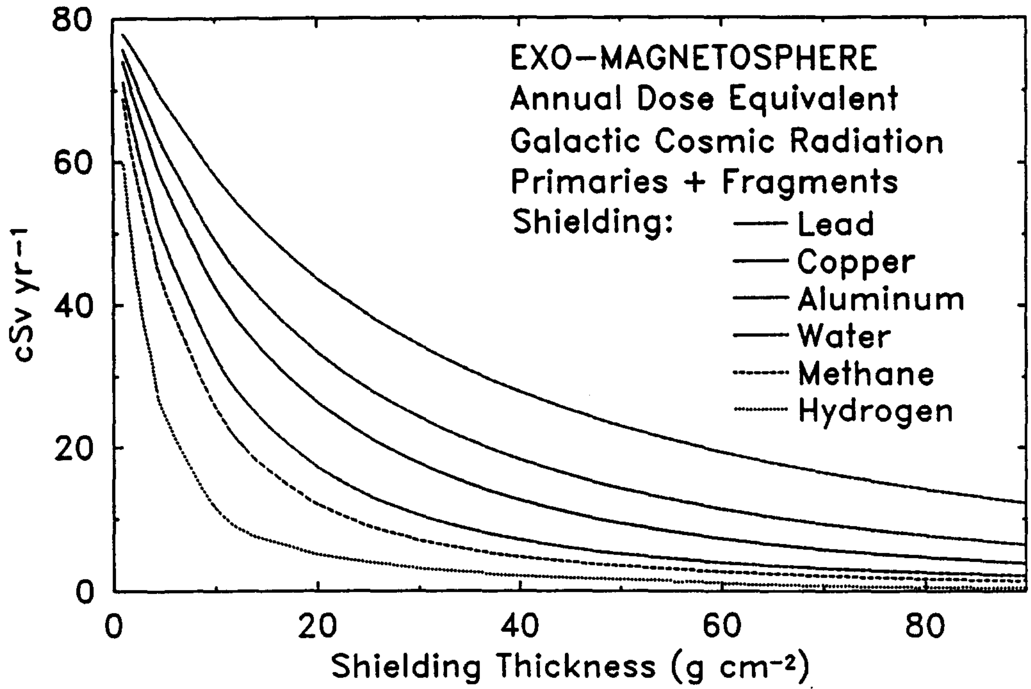

Figure 4: Annual dose equivalent from galactic cosmic radiation as a function of shielding thickness for several possible spacecraft shielding materials.

We note immediately the extraordinary difference in attenuation of galactic cosmic radiation by these six materials. Hydrogen, with the lowest atomic mass, provides by far the best shielding of GCR. Lead, with the greatest atomic mass of the group, is the worst of the shields.

The differences in shielding properties stem from three factors. First, the nuclear fragmentation cross sections on different target materials increase roughly as the square of the radius of the target nucleus (atomic mass $A^{2/3}$). On the other hand, the target mass increases as A. Hence, per unit mass, lower atomic mass materials offer more surface cross section for nuclear fragmentation. The second effect is the ionization losses which increase roughly as the number of electrons (Z) available in the material. Once again, the mass increases as A, which grows faster than Z because of neutrons. Hence, lighter materials provide more electrons per unit mass and are more effective at slowing heavy ions. The third factor, production of secondary neutrons, also favors light nuclei which are relatively neutron poor.

From Figure 4 we have derived a formula for estimating the aluminum shielding equivalent (X) of any thickness, x g cm^{-2}, of another material having mean atomic mass, $\bar{A}$. Thus,

$$\ln X = 1.16 + (0.977 + 0.018 \ln \bar{A}) \ln x - 0.371 \ln \bar{A}$$

for $\bar{A} > 1$ and

$$\ln X = 1.47 + 0.966 \ln x$$

for $\bar{A} = 1$ (hydrogen). This formula represents our data to within 10% for shielding in the range $0.5 \text{ g cm}^{-2} \leq x \leq 80 \text{ g cm}^{-2}$.

For rough estimates, the equivalent aluminum shielding for any thickness of H, CH_4, H_2O, Cu(Fe) or Pb may be obtained by multiplying by 4.35, 2.07, 1.64, .684 or .441, respectively. Thus liquid hydrogen shielding is equivalent in effect to 4.35 times its weight (or thickness in g cm^{-2}) of aluminum. Approximately 50% more iron (nearly the same in effect as copper) than aluminum is required to produce the same level of radiation protection.

ADDITIONAL ENVIRONMENTAL FACTORS

Other factors pertinent to the assessment of radiation risks on missions outside the magnetosphere, some of which have been discussed in previous reports, are reviewed briefly here.

A typical interplanetary mission will involve three exo-magnetospheric phases. During the *interplanetary phase*, the spacecraft is exposed to unattenuated particle fluxes from GCR and SPEs. There is no safe haven so all protection must be provided within the spacecraft.

During the *orbital phase*, the spacecraft is close to the planet. It is protected from some (< 50%) of space radiation by the "shadow" of the planet. The transmission factor for space radiation is given by $(1 + \cos\Theta)/2$ where $\sin\Theta = R_{Planet}/R_{Orbit}$. It is possible that a safe haven on the planetary surface could be reached within a matter of hours.

During the *surface phase*, the astronaut is fully shielded from 50% of space radiation by the "shadow" of the planet. The annual BFO dose equivalent from GCR on the Moon is therefore about 0.25 Sv, one-half of the free space dose equivalent. Additional shielding may be provided by the atmosphere of the planet. For example, the atmosphere of Mars has about 1% of the pressure of the Earth's atmosphere or 10 g cm^{-2} of CO_2. This is sufficient to reduce the radiation dose by an additional factor of two (from the dose on the lunar surface) to about 0.12 Sv yr^{-1} /21/.

Permanent or emergency radiation protection on planetary surfaces may be obtained underground. About 2 m of lunar soil is required to bring the annual dose equivalent down to 0.005 Sv, the limit for terrestrial radiation workers /22/. 5 m to 10 m of lunar soil is required to reach natural terrestrial radiation levels.

The mean cosmic-ray intensity and the frequency of solar energetic particle events are variable and are correlated with the general level of solar activity. Solar activity, as measured by sunspot number, has a period of approximately 11 years. Other long-term periodicities occur in the sun, for example, magnetic fields vary over 22-year cycles. During solar maximum cosmic rays below 1 GeV per nucleon are attenuated in the heliosphere. At that time the dose equivalent from galactic cosmic radiation may be a factor of two lower than at solar minimum. The years between solar maximum and solar minimum show an irregular, but roughly monotonic, increase in cosmic-ray intensity.

Large solar particle events occur with much higher probability during solar maximum than during solar minimum. However, on purely statistical grounds it is incorrect to conclude that large SPEs do not occur during solar minimum. Measurements of SPE intensities in space comprise only two full solar cycles. There was one anomalously-large SPE during that time (August, 1972).

A reduced risk of SPEs and a consequent lessening of massive shielding requirements may be engineered by restricting long-duration missions to solar quiet times which constitute possibly one half of the solar cycle. The advantages of this compromise must be weighed carefully against increased exposure to cosmic-ray heavy ions and the drastic reduction in launch window which would result. For a three-year Mars mission to take place during a five-year solar minimum, the launch window is only two years. The relative positions of Earth and Mars would allow only two launch opportunities within that two-year window. Failure to achieve launch would result in an 11-year delay in the mission.

SUMMARY

An assessment of radiation doses and shielding requirements for exo-magnetospheric space missions has been presented. We find that lethal radiation doses are not expected from anomalously-large solar particle events as intense as the August, 1972 event. The onset of early radiation effects from a SPE is prevented by supplying a storm shelter having > 7 g cm^{-2} aluminum shielding on all sides. If, in the future, recommended radiation exposure limits similar to those made for the space station /16/ are imposed on deep space missions, then the required storm shelter shielding could increase to 25 g cm^{-2} of aluminum.

Galactic cosmic radiation doses are within NCRP monthly and annual recommendations. No additional shielding is required to protect the astronauts. Age and sex of participating crew members or mission duration may be restricted by career dose limits. If a safety factor of 2 is required, then it is practically impossible to supply the necessary aluminum shielding to remain within NCRP recommendations. Other shielding materials are available and have been considered.

Hydrogen (liquid or gas) is equivalent in shielding effect to 4.35 times its mass in aluminum for shielding GCR. It is the ultimate GCR shielding material. Methane, water, copper (iron), and lead are equivalent to 2.07, 1.64, 0.684 and 0.441 times their mass in aluminum, respectively. Similar factors apply for shielding of protons from SPEs.

We find that missions outside the magnetosphere are feasible. There is a high probability of an anomalously-large SPE which must be planned for. A storm shelter having at least 7 g cm^{-2} of aluminum shielding should be mandatory on all long-duration exo-magnetospheric missions. Additional shielding may be required to insure that long-term cancer incidence is held below acceptable limits.

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