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Radiation Shielding Requirements for Manned Deep Space Missions

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ABSTRACT

Galactic cosmic rays (GCR) and, particularly, solar flares (SF) constitute the major radiation hazards in deep space. The dose to astronauts from these radiation sources and the shielding required to mitigate its effect during a 480 day Mars mission is estimated here for a simplistic spacecraft geometry. The intent is to "ball park" the magnitude of the doses for the constant GCR background and for SF's that occur randomly during the mission. The spacecraft shielding and dose data are given only for primary GCR and SF radiation, recognizing that secondary particles produced by primary particle reactions in the spacecraft and High Z-High Energy particles will also contribute to the dose suffered by the astronauts.

I. INTRODUCTION

The radiation environments be encountered in deep space missions will impose demanding problems on spacecraft shield design in order to insure astronaut survival, protection of life support systems, and sustained operation of essential electronic and computer systems. Radiation protection of humans and equipment will be complicated by the diverse and sometimes unpredictable nature of the radiation fields outside of the earth's geomagnetic field. The potential for life threatening radiation will compel spacecraft designers to carefully optimize and configure radiation shields to achieve maximum protection while simultaneously minimizing spacecraft weight. In addition, the shielding must also be compatible with that used for meteoroid protection, thermal control and heat exchange requirements, and the overall structural integrity of the spacecraft. In combination, these constraints may constitute the leading feasibility concern for the proposed human exploration of Mars.

The relatively uniform cosmic radiation hazard in space will become important as mission durations increase. In addition, the potential for occurrence of large solar flare events, which will pose the greatest hazard to spacecraft occupants and equipment, may also dictate inclusion on the spacecraft of heavily shielded shelters where the astronauts and their life support and navigation systems can find refuge from intense and energetic, albeit relatively short duration, solar flare radiation.

Radiation protection guidelines for manned space missions have not undergone official revision since 1970 although radiation protection criteria have, to some extent, been revised as new missions have been introduced and as approaches to radiation protection have changed.[1] Currently, the overall career limit on exposure in space for astronauts in their mid-thirties is 400 rem, based on a doubling of their natural cancer risk in the ensuing 20 years. This corresponds, approximately, to an annual average dose rate of 20 rem per year which exceeds the presently accepted annual dose rate for radiation workers by a factor of four and is forty times greater than the annual dose rate recommended for the general public. Recent risk studies suggest annual exposure guidelines should be reduced by a factor of 10, and in addition, a radiation management strategy must be implemented to keep doses As Low As Reasonably Achievable. An excellent review of the radiation protection criteria and the effects of space radiation is found in Ref. 1 and in the references contained therein.

The purpose of this paper is provide a concise description of the primary radiation hazards in space and to "ball park" the kinds of radiation doses which might be received on a typical manned mission to Mars. A short review of the sources of radiation that will be encountered in a deep space mission is given in Section II. A plausible Mars mission is described in Section III, including a description of a simplistic spacecraft model. In Section IV, the potential dose levels from the various radiation sources are estimated for a variety of radiation sources and shielded configurations. Finally, some observations, concerns, and cautions that should be noted in reviewing this summary are discussed in Section V.

II. SPACE RADIATION ENVIRONMENTS

Three radiation environments will be encountered during a flight to Mars and back: the radiation trapped in the earth's magnetic field, i.e., the Van Allen Belts, galactic cosmic rays, and the charged particles from solar flares.[2,3] Depending on the mission profile, trajectory, and duration, each of these sources will contribute to personnel and equipment doses.

Van Allen Belt Radiation:

When the distribution of trapped particles in the earth's magnetic field are examined, two reasonably distinct zones - the inner and outer Van Allen Belts (VAB) - may be distinguished.[4] The inner belt is comprised mainly of protons with energies extending to several hundred MeV. The outer belt is predominately electrons with energies up to several MeV. The inner belt extends to about 2.8 R_e (R_e = one earth radius = 6.4 x 10^3 km) while the outer belt occupies the space between 2.8R_e and 12R_e. The belts occupy a distorted toroid about the earth and lie in the plane of the geomagnetic equator. The energy and spatial distribution of the particles in the belts, particularly the electrons, undergo both regular and stochastic variations with time. It should be noted that electrons are also found in the inner belt, but the electron intensities are smaller (~ 0.1) than those in the outer belt and their energies are also lower. Inner belt electrons are generally ignored in shielding calculations.

The time averaged spatial distributions of the protons in the inner belt with $E_p > 100$ MeV, shown in Figure 1, exhibit a sharp rise starting at $\sim 1.16R_e$ and reaches a maximum at $\sim 1.5R_e$ with an integral fluence of 10^4 protons/cm^2. The proton flux then drops off slowly to a flat maximum at about 2.2R_e and then drops rapidly to a level of 10^2 protons/cm^2 at an altitude of $\sim 2.8R_e$. The electron intensity ($E_e > 40$ keV) peaks at 10^9 electrons/cm^2 at $\sim 3.5R_e$.

The proton and electron fluxes are each a strongly varying function of altitude and location about the earth. In the vicinity of 35° south latitude and 325° east longitude, in the area referred to as the South Atlantic Anomaly,[5] the flux of trapped particles are larger than at anywhere else at the same altitude. At 370 km altitude, the fluence of protons with energies in the range $40 < E_p < 100$ MeV are as much as 1000 times larger than elsewhere in the belt at the same altitude. Similar spatial behavior has been observed for the electrons.

The omnidirectional proton and electron fluxes (typical) as a function of particle energy are compared in Figure 2. As altitude increases, the electron spectrum softens while the converse is true for protons, at least to altitudes up to 2.2R_e. In terms of the energy to mass ratio, E/m, the shapes of the proton and electron spectra are very similar.[6]

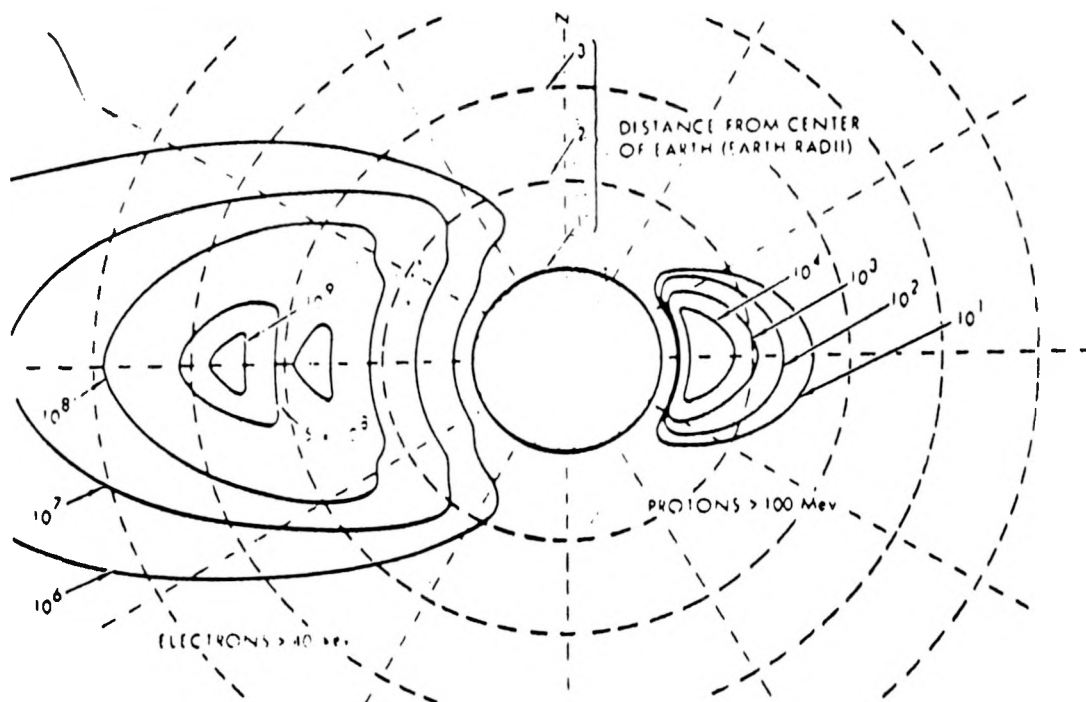Figure 1. Spatial Extent of Trapped Electrons and Protons
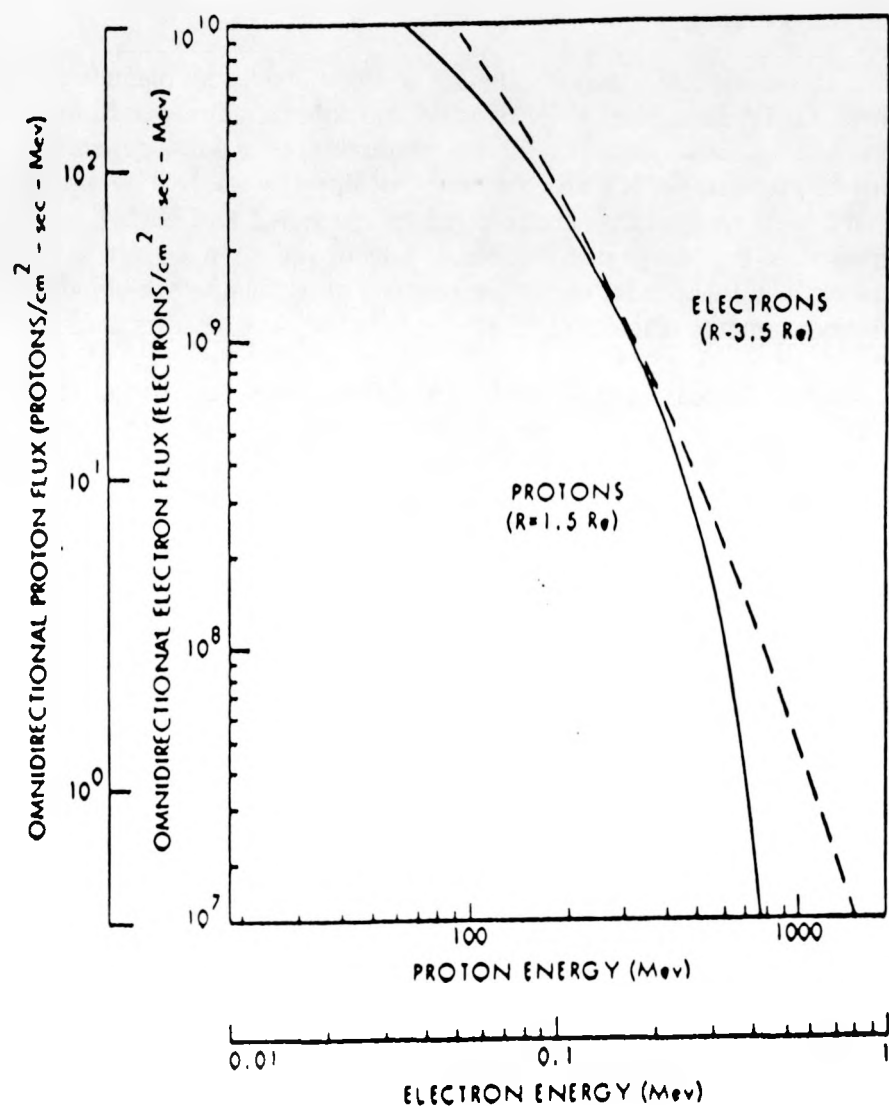Contours. (in units of particles/cm^2.)

Figure 2. Comparison of Van Allen Belt Proton and Electron
Differential Energy Spectra

Galactic Cosmic Ray Radiation:

Galactic cosmic rays constitute a major radiation source outside the magnetosphere.[6,7,8] Galactic cosmic rays (GCR) have been widely studied and considerable literature is available on the subject. From the point-of-view of radiation protection, only a few general properties of cosmic rays are of interest. GCR's are composed of approximately 87% protons, 12% alpha-particles, and 1% heavy ions that are referred to as High-Z and High-Energy (HZE) particles. A comparison of the charge distributions in galactic radiation is given in Table 1.[6,9] Of the HZE particles, iron is the most important because of its relatively high abundance in GCR and its high linear energy transfer (LET).

GCR energy spectra decrease rapidly with increasing energy but extend to very high energies (up to 10^{20} ev). Since the sources of GCR particles are outside the solar system, their distribution throughout space is essentially isotropic. The differential energy spectrum of GCR protons exhibits a broad maximum in the energy region near 1 GeV. At energies below 100 MeV/nucleon, the spectra decrease in intensity due to partial shielding by the particle interactions with the "solar wind"; the highly ionized gas that is emitted from the sun. The spectra of alpha particles and HZE particles have essentially the same behavior with energy as the proton spectrum except the maximum occurs at about 300 MeV/nucleon. GCR proton, alpha-particle, and HZE ion fluxes vary inversely with the 11-year solar activity cycle. At maximum solar activity, the GCR intensity is a minimum but slowly increases during the cycle until solar minimum is reached. Short term variations in cosmic-ray intensities occur between cycles, but these are small when averaged over the cycle duration and are not pertinent to spacecraft shield design. For shield design purposes, the solar-maximum and solar-minimum spectra can be taken as the upper and lower limits of the particle fluxes that will be encountered outside the earth's magnetosphere. Figure 3 shows the integral solar-minimum and solar-maximum proton, alpha-particle, and heavy ion fluxes per unit energy per nucleon. The maximum particle fluence rate of GCR radiation at solar minimum is of the order of 4 cm^{-2} s^{-1}.

Solar Flare Radiation:

Spaceflight missions beyond the vicinity of earth will absolutely require that the occupants and the radiation sensitive equipment in and on the vehicle be shielded against the short term but intense and energetic charged-particle radiation from solar flares. These particles constitute the greatest radiation danger that will be encountered in deep space.

Solar-flare radiation is composed chiefly of protons with a varying number of alpha particles and an mixture of heavier ($Z > 2$) nuclei. The characteristic fractions of these charged particles vary between flares as well as within a flare and as a function of time. Protons have been detected in all flares and considerable studies have been made of their energy spectra and intensities. The alpha-particle component observed in solar flare radiation has also been widely studied. The heavy ion component of flares has been reviewed by Fitchel and Guss[10] and by Ney and Stein[11]. Their data indicates that the carbon-nitrogen-oxygen (CNO) group appears to be the dominant portion of the heavy particles that combine to constitute about 0.1% of the total flare radiation.

Table 1. Comparison of Charge Distributions in Galactic Radiation

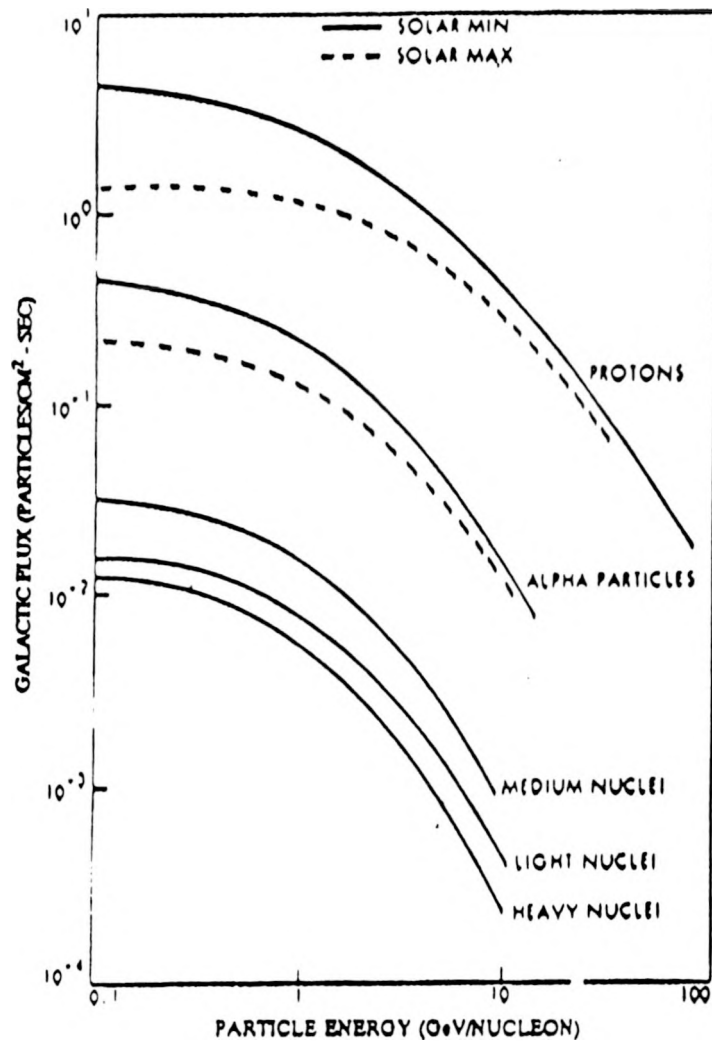| Element Group	Intensity (Particles/cm^2 - sec)	Atomic Abundance (% by number)
Hydrogen (Protons)	3.6	88
Helium (Alpha Part.)	4×10^{-1}	9.8
Light Nuclei (Li-B)	8×10^{-3}	0.2
Medium Nuclei (C, N, O, F)	3×10^{-2}	0.75
Heavy Nuclei ($10 \leq Z \leq 30$)	6×10^{-3}	0.15
Very Heavy Nuclei ($Z \geq 31$)	5×10^{-4}	0.01
e$^-$ and γ (E > 4 GeV)	4×10^{-2}	1

Figure 3. Integral Energy Spectra for the Various
Components of Galactic Cosmic Radiation

The intensity, energy spectra, and angular distributions of solar-flare protons and alpha-particles vary widely from event to event and as a function of time within an event.[12] The duration of a typical flare is of the order of one to four days although flares of somewhat longer duration have been observed. The flare builds up rapidly during the first several hours and then decreases steadily. During the early stages, the particle angular distribution is anisotropic but rapidly tends towards isotropy and, from a shielding point-of-view may be considered isotropic during most of the flare interval. The time-integrated solar-flare energy spectra are represented by exponential functions of magnetic rigidity where the magnetic rigidity, P_j, is defined by[12]

$$P_j = p_j c / z_j e,$$ (1)

where
p_j = particle momentum,
c = velocity of light,
z_j = the charge number ($z_{proton} = 1$, $z_{alpha} = 2$)
e = electronic charge.

The omnidirectional fluence of solar flare particles above kinetic energy E may be obtained from

$$J_j(>E) = J_{oj} \exp(-P_j(E)/P_o), \quad j = proton, alpha-particle$$ (2)

where
$J_j(>E)$ = the number of protons or alpha particles per unit area in the flare having kinetic energy $>E$,
$P_j(E)$ = the magnetic rigidity given by Eq.(1),
J_{oj}, P_o = parameters that characterize a particular flare.

Modisette[13] has shown that P_o varies from 50 to 200 MV (mega volts) and that the total number of protons with energies greater than 30 MeV varies from ~10^6 to ~10^9 protons/cm^2. More recent data shows evidence of flares with greater than 10^{10} protons/cm^2. Figure 4 shows the solar flare proton and alpha-particle fluence as a function of energy (E > 30 MeV) for flares having characteristic rigidities of 50, 100, and 200 MV. Figure 5 compares the time-integrated spectrum of the August 4-7, 1972 flare with GCR proton spectra accumulated during one week both for solar minimum and maximum conditions. The flare's relative radiation hazard to astronauts on missions outside the earths's magnetic field is apparent.

The difficulty in designing shielding for deep space exploration systems is the uncertainty in the occurrence of solar flares and the magnitude of the radiation that will be emitted. Eight to thirteen flares can be expected to occur annually. Rust[14] points out in his paper that "*In some orbits, there is no reasonable level of shielding material that will protect shuttle occupants from potentially lethal doses of this (solar flare) radiation.*" In this case the orbits are polar orbits around the earth where the magnetic field is minimum. The same condition exists in deep space where the shielding by the earth's magnetic field is absent.
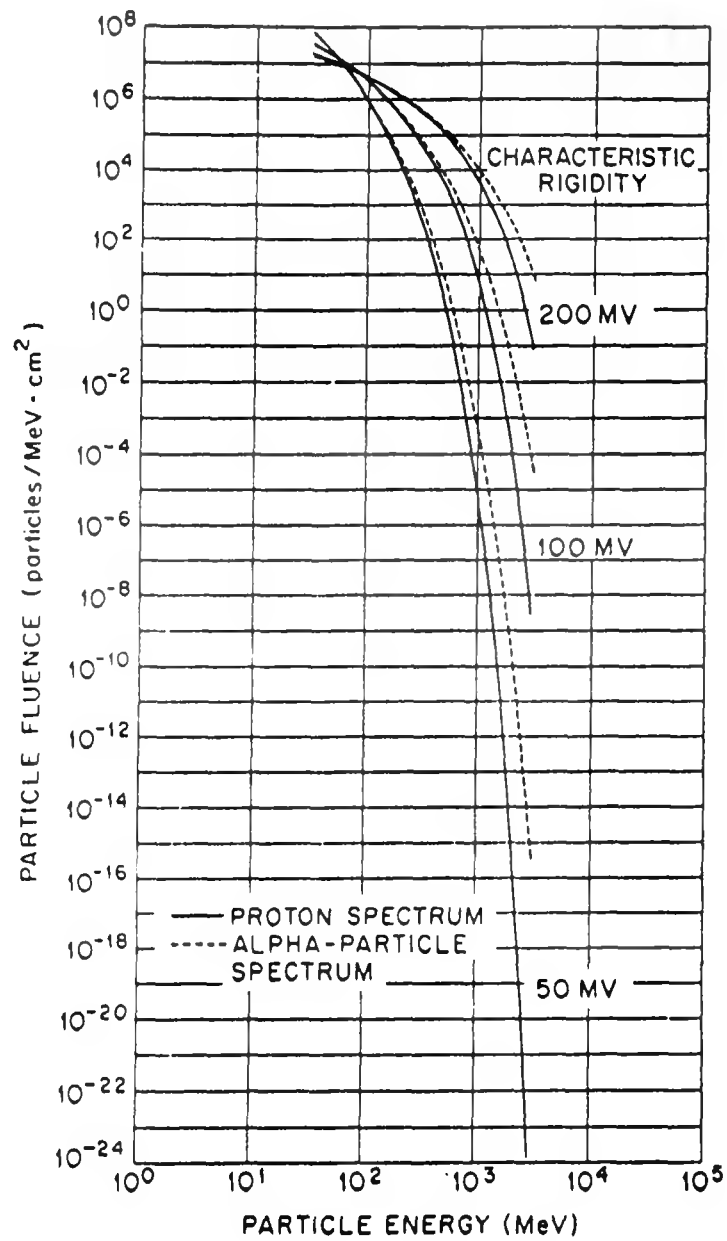
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Figure 4. Solar-flare Proton and Alpha Particle Spectra
as a Function of Characteristic Rigidity
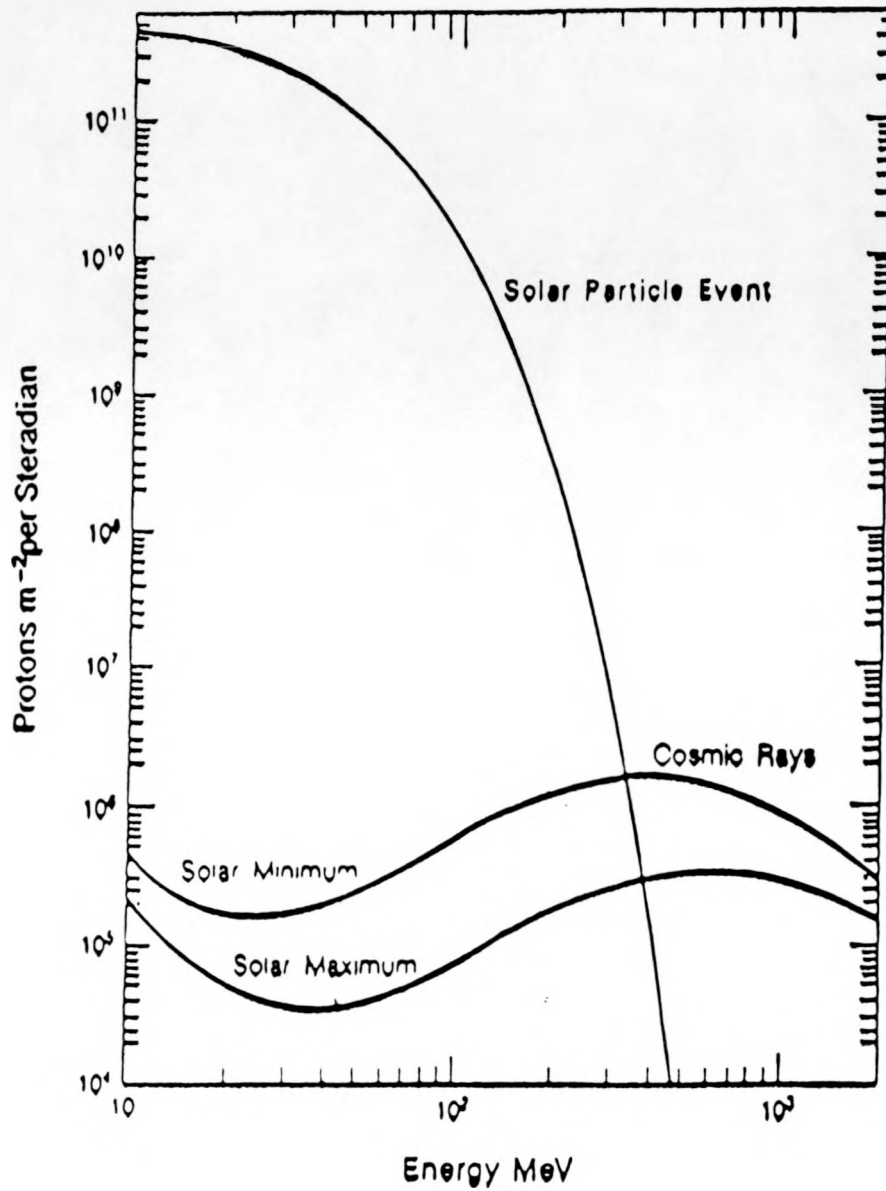(Normalized to 10^9 Particles/Flare)

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Figure 5. Comparison of the Time-Integrated Differential Energy Spectrum of Protons for the Solar Flare of August 4-7, 1972 with the spectra of GCR protons accumulated in one week. (Silberberg, et. al.,[16])

III. A MARS MISSION

To gain insight into the shielding requirements for deep space mission, we assumed a 480 day Mars scenario, which is plausible assuming present launch technology.[6] A shorter mission would require a larger incremental boost velocity to inject the spacecraft into a Mars trajectory while a mission of longer duration would increase the life support system specifications and meteoroid and radiation shielding requirements. The mission scenario is as follows

> 220 day flight to Mars,
> 30 day Mars orbit/surface exploration, and
> 230 day return trip and re-entry.

The amount of spacecraft shielding required for a Mars mission of this duration is estimated based on the current available literature and on numerous studies that have been carried out for prototypic spacecraft geometries. Additional data have been deduced assuming a simplistic spherical shell model for the spacecraft, including a central sphere of tissue or other materials to simulate the desired dose response. Given the virtual absence of information on potential vehicle designs and mission architecture, this simplifying assumption is a plausible model for estimating dose and shielding requirements in the absence of specific geometry effects. Obviously, major perturbations in the dose could be caused by including the effects of other spacecraft components, streaming paths, etc.

IV. SPACECRAFT SHIELDING REQUIREMENTS

The dose suffered by the astronauts during this Mars mission will be discussed for two shielding possibilities. First, the spacecraft is assumed to be uniformly shielded with 5 g/cm^2 (1.85 cm) aluminum over the entire surface and second, shielding is added as needed to reduce the dose to acceptable levels. To estimate the relative shield weights, the spacecraft is taken to be a sphere with an inner radius of 5.5 m. This corresponds approximately to a spacecraft having a volume four times that of the Shuttle bay. Covering the outside with a 1.85-cm-thick layer of aluminum results in a total shield weight of ~19 metric tons.

The first radiation that will be encountered in the mission will be from VAB protons and electrons. If insertion into a Mars trajectory occurs at an altitude of 1.5R$_e$ and the trajectory is equatorial superimposed on the spatial distribution of the proton and electron belts and the time integral of the particle fluxes are calculated, then the spacecraft will be subjected to approximately 1 x 10^{12} electrons/cm^2 above 40 keV and approximately 6 x 10^6 protons/cm^2 with energies above 100 MeV. Haffner[6] has shown that the resulting proton and electron doses to the astronauts shielded by aluminum as described above during escape from earth orbit are 1.4 and 0.27 rad, respectively. The relative biological effectiveness for protons attenuated by 5 g/cm^2-thick aluminum is 1.1, so the biological dose at a point inside the shield is 1.7 rem. The value given for the proton dose is consistent with the dose calculated by Alsmiller, et. al.[13] for the same altitude. The VAB dose on the return leg will be slightly higher than on the outgoing leg due to anticipated waiting times in orbit to find an appropriate earth re-entry window. Consequently, the total VAB dose for the mission is taken to be approximately 3.6 rem.

The GCR dose rate will depend on the time that the mission is initiated relative to the solar maximum or minimum. If the mission is initiated at the peak of the solar maximum cycle, the biological dose rate behind the shield will be of the order of 20 rem/y. For a flight beginning at the solar minimum, the dose rate increases by a factor of 2.5, yielding 50 rem/y. Hence, for the mission assumed here, the GCR induced biological dose will range between 26 and 66 rem. The dose rate will be a slowly increasing or decreasing function of time during the flight. For a 1.85-cm-thick Al shield, the dose is due mainly to primary protons with only a relatively small contribution arising from secondary particles produced by primary particle reactions in the shield. The contribution from HZE particles is not included in the GCR dose estimate.

The estimated GCR dose is considerably larger than the annual 0.5 rem limit recommended for the general population on earth. Hence, selection of astronauts (age, physical condition, sex, etc.) and the consequences of substantial radiation exposures must be carefully evaluated in terms of immediate and protracted biological effects. The combined VAB and GCR dose of nearly 70 rem also exceeds the current regulatory limit for occupational exposure, and as will be indicated below, is still a relatively minor concern compared to the most serious problem: solar flare radiation.

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The difficulty in estimating the shielding to protect astronauts against solar flares lies in the uncertainty of flares events. Letlaw, et. al.,[15] note that for each week in space outside the earth's magnetosphere there is a 1 in 500 chance that <u>unshielded</u> astronauts will receive a lethal dose from solar flare radiation. Since flares occur semi-randomly, it is also not possible to accurately predict the when a flare will occur or its size. What is feasible, however, is the prediction of the probability that a given solar flare flux or dose will be exceeded during a specified period of time. Weber, Modisette, et. al., and others have established dose versus probability curves for the flare period between 1956 and 1961 (based on 60 solar events). Figure 6 shows the dose-probabilities averaged over this solar event cycle as a function of aluminum shield thickness. Assuming that the dose data in Figure 6 scale exponentially with shield thickness and that differences in proton energy cutoff due to the change in shield thickness can be ignored, then for 10% flare probability, astronauts protected by a 1.85-cm-thick aluminum shield will receive a total dose (from protons and alpha particles) in excess of 600 rem during the 14 month mission. The current nominal value for LD50, i.e. the dose level corresponding to a 50% survival likelihood, is 450 rad for whole body exposure (295 rad bone marrow dose). Although this value varies with such things as health, treatment, dose rate, etc., considerable biological impact and performance degradation can be expected for this level of dose. Clearly, a total mission dose of 670 rem is unacceptable.

The data used to construct Figure 6 are based on a single flare cycle. Several solar cycles have ensued since these data were acquired and have contained large flares that will alter these probabilities. However, the serious consequences of flare radiation are clearly illustrated and the possible dose levels that will be received by the astronauts during a Mars mission in an inadequately shielded spacecraft is demonstrated. Deep space mission will demand that astronauts be isolated from solar flare radiation by much thicker shielding that is either disposed over the entire surface of the spacecraft or in the form of a shielded shelter located inside the spacecraft. The size of the shelter will depend on the number of astronauts to be protected combined with the requirements for isolating radiation sensitive life-support equipment and organisms, electronics, and flight control systems in the event that the flare occurred at a critical period, e.g., at a course correction, during entry into Mars orbit, prior to reentry back into earth orbit, etc. With these considerations in mind, the second course of action is reviewed where shielding is added to reduce the dose.

From Figure 6, it can be estimated that doubling the thickness of the shielding to 3.7 cm (10 g/cm^2) results in a reduction of the 10% probable flare dose from the unacceptable 600 rem level to approximately 200 rem. However, the shield weight penalty is significant, resulting in an increase in the shield weight of 19 metric tons and yielding a total spacecraft shield weight of 38 metric tons and a dose which is still unacceptably high.

Several investigators have suggested that the habitable areas of deep space mission spacecraft be shielded with a minimum of 20 g/cm^2 aluminum (or its equivalent). If spread uniformly over the entire spacecraft, the increase in weight over the our reference configuration is ~60 metric tons, resulting in an overall shield weight of ~78 metric tons. Alternately, a storm shelter concept could be adopted, which would provide added protection
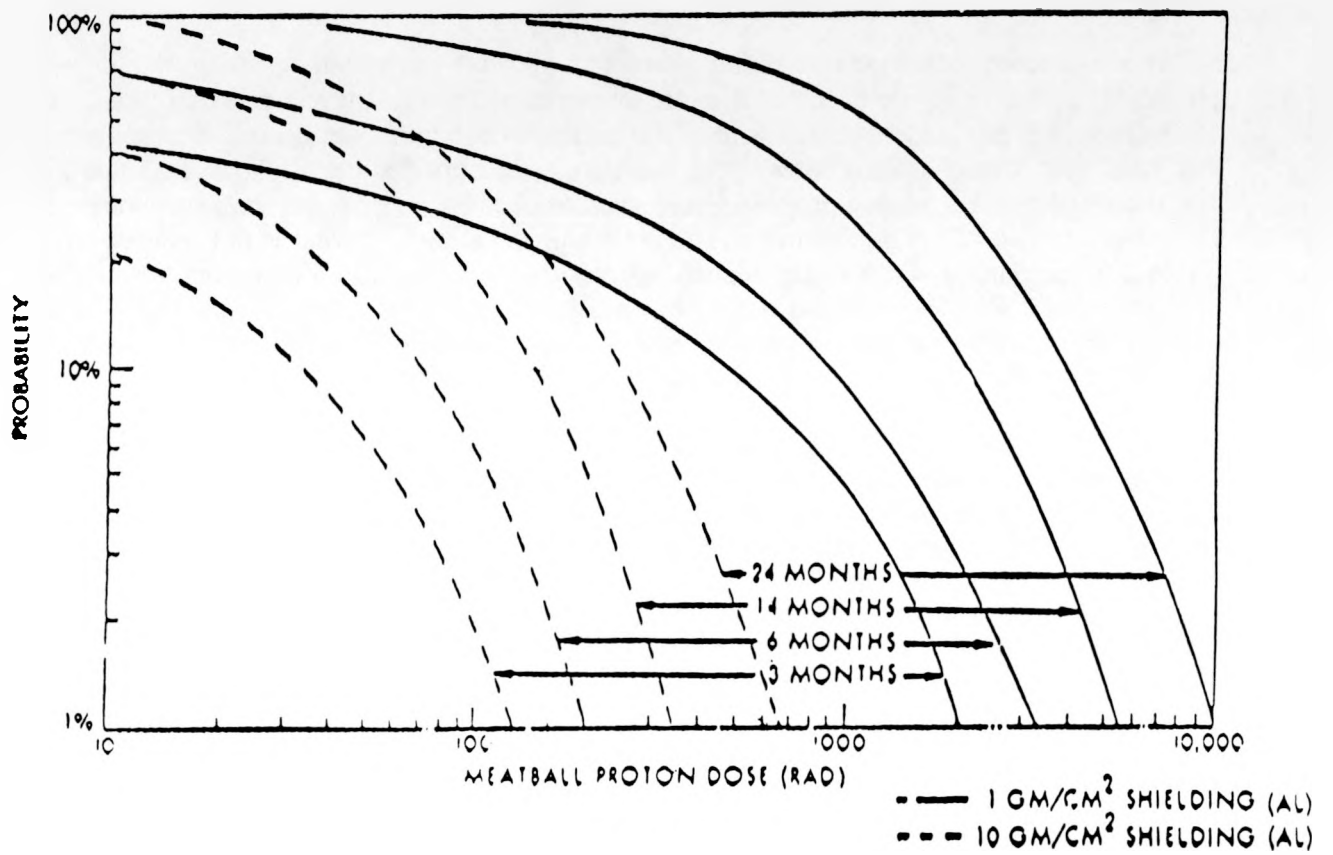
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Figure 6. Solar Flare Dose Probability

for just a portion of the spacecraft. In our simplistic model, a plausible shelter might consist of a sphere of 2 m radius surrounded by 15 g/cm² Al located inside the main spacecraft. The added shield weight is 7.8 metric tons, yielding an overall shield weight (including 5 g/cm² Al outer shield shell) of only ~27 metric tons while still providing an effective shield thickness for solar flare protection of 20 g/cm². This amount of added shielding would decrease the solar flare dose by about a factor of 100.

The estimated doses and shielding discussed above were obtained using the dose-probability curves in Figure 6. These data are averages over the solar cycle between 1956 and 1961. Langham has made a comparison of the maximum and minimum dose as a function of the "best" and "worse" launch dates[15] for this flare cycle period which is shown in Table 2. For the 480 day Mars mission proposed here, the dose behind a 1 g/cm² Al shield can vary by factors of ~10 to ~140 depending on the launch time. However, what is not indicated in Table 2 is the narrow width of the launch window that will result in a minimum dose. To achieve a dose of ≤15 rem during a one year mission in this cycle required that the launch occur during the six-week period between mid-July and the end of August, 1959. It is safe to assume that similar constraints will occur for deep space launches during future solar cycles.

It is reasonable to expect that astronauts traveling to Mars and back for 480 days will be exposed to the radiation from eight to thirteen flares. Figure 7 shows the dose from a single flare as a function of magnetic rigidity for shields having thicknesses of 5 and 20 g/cm². The proton and alpha-particle curves have been normalized to 10^9 protons/cm² (E > 30 MeV/nucleon). If a single flare with a characteristic rigidity of 125 MV occurs, the astronauts in a 5 g/cm² aluminum shielded spacecraft would receive a total dose of 285 rem (~200 rem proton and 85 rem alpha-particles). A 20 g/cm²-thick shield would reduce the corresponding dose to approximately 14 rem. Although the size distribution of flares is unpredictable, it is likely that the total solar flare dose from a Mars mission will be substantial due to one or two "big ones" such as the 125 MV flare mentioned above, with the remaining flares contributing relatively little additional dose.

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Table 2. Maximum and Minimum Mission Doses*

For Best and Worst Launch Dates In

Solar Cycle 19

Mission Duration	Maximum Dose (rad)	Minimum Dose (rad)
4 years	3492	2439
3 years	3229	974
2 years	2781	526
1.5 year	2415	176
1 year	2110	15
9 months	1963	2
6 months	1962	0
3 months	1962	0
1.5 months	1492	0
1 month	1452	0
2 weeks	1492	0
1 week	1492	0

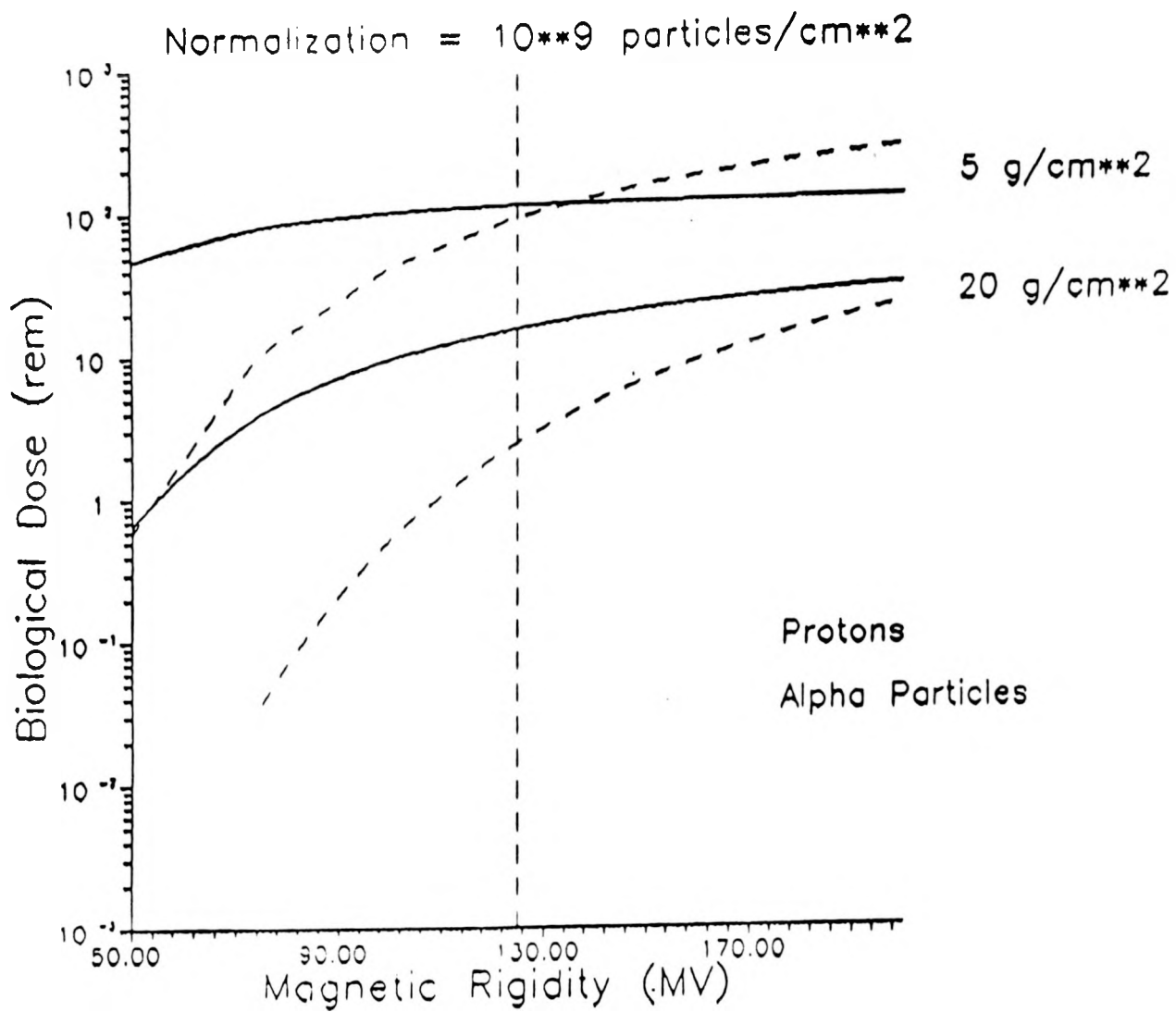* Surface dose inside 1 g/cm^2 uniform aluminum shielding.

Figure 7. Biological Dose versus Flare Magnetic Rigidity
for 5 and 20 g/cm² Thick Shields

V. DISCUSSION

The estimated dose and shield weight results given above are for a very idealized spacecraft geometry. Accurate estimates of the hazards to deep space voyagers must await more detailed spacecraft design data and proposed mission scenarios. However, the radiation threat to astronauts is clear. Precautions and detailed studies must be taken to assure adequate shielding to achieve ALARA dose levels to both male and female astronauts. Considerable research must be carried out to develop and test new shielding concepts and analysis tools to support design of manned planet exploring spacecraft.

The preliminary and cursory results given here are for primary radiation only. No consideration was given to the dose from secondary particles produced from the reactions of energetic GCR and solar flare particles in the shield and other materials in the spacecraft. Secondary particle will lead to severe doses particularly for those particles and radiation modes characterized by high RBE and LET values. Migration of the primary radiation through the materials in the spacecraft may generate copious quantities of secondary particles that must be carefully estimated using accurate representation of the spacecraft geometry particularly where the particles pass through different materials before coming to rest.

Also, no consideration was given to the effects of radiation on electronics, computers, solar panels, on-board reactor components, life support systems, seals, windows, or any of the other scores of components whose performance may be degraded by radiation. Minimally shielded components located outside the primary vehicle shield will sustain very large doses from flare and GCR radiation. Deep space manned systems will have to carry instrumentation to observe solar activity or the unexpected on-set of radiation that may indicate the arrival of flare radiation.

What has been attempted here is to identify and approximately characterize the hazards to Mars explorers of GCR and solar particle radiation in space. What is omitted are detailed considerations of biological effects including those arising from HZE particle reactions in critical organs where the consequences of even a few HZE reactions may be dramatic. No attention has been paid to the radiation effects on males and females and the potential for cancer induction or detrimental effects to potential offspring.

Finally, efforts are still required to obtain measured data for validating calculations of the effects of prolonged space travel combined with prompt and protracted radiation doses in weightless environments and deep space in general.

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