Solar Flare Radiation Protection Requirements for Passive and Active Shields

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The degree of protection from solar flare radiations required by astronauts on a typical interplanetary flight is investigated if the protection is provided by a) active means (plasma radiation shielding), or b) passive means (bulk shielding). Anticipated solar flare radiation environments as proposed in several recent studies are used to relate absorbed dose at two body sites, the skin and the blood-forming organs, to the parameters of the two shielding concepts. Curves are generated of dose vs passive shield thickness and plasma radiation shielding voltage with probability of exceeding a given dose as a parameter. Maximum permissible dose levels at the two body sites of interest, and allowable probabilities of exceeding these dose levels during the missions, are specified. Requirements for the two types of shielding are tabulated. A limited comparison is made between the requirements for the two types of shielding, and data are provided for eventual broader comparisons of spacecraft that embody the two types of protection.

Nomenclature

D = radiation dose
E_0 = energy of proton in free space
E_1 = energy of proton inside of shield
$F(>E_0)$ = integrated flux of protons with energy greater than E_0
f = exposure nonuniformity modification factor
G = event flux parameter
M = rest mass energy (= 938 Mev for protons)
P = magnetic rigidity
q = particle charge (= 1 for protons)
V = plasma radiation shield potential
X = shield thickness
$\phi(E)$ = differential flux distribution function

Subscripts

a = area
c = event characteristic
p = depth
r = rate
v = volume

Introduction

PROTECTION against the hazards posed to astronauts on deep space missions by ionizing radiations can be afforded in two basic ways which may be categorized as "passive" or "active" methods. Passive methods consist of placing radiation-absorbing material around the cabin to reduce the radiations incident on the astronauts to acceptable levels. The sizeable thickness (and weight) required usually dictate that only a minimum-size "storm cellar" be protected. Active concepts utilize electrostatic and/or magnetic forces to deflect the charged-particle radiations away from the spacecraft. Several such concepts have been advanced but investigation has shown that the only one that combines the promises of reduced shielding weight and elimination of the disadvantages of a storm cellar with a reasonable expectation of success is the plasma radiation shield (PRS).

The PRS concept has been described in Ref. 1 and its application to manned spacecraft in Ref. 2. Very briefly, the plasma radiation shield is an electrostatic shield with a shielding voltage maintained between the positively charged spacecraft and a surrounding cloud of free electrons. The cloud of electrons is held in place by a magnetic field, and the outer edge of the cloud is at the potential of free space. The charges on the spacecraft and the electron cloud are equal and opposite, so that the arrangement can be considered as a capacitor.

The potential advantages offered by the PRS make it desirable to compare its shielding requirements (in terms of voltage) with those of a passive system (in terms of material thickness) for similar spacecraft missions. Such a comparison first requires hypothesizing both a typical manned interplanetary mission and an anticipated radiation environment.

The assumed mission duration is 1.5 years near the peak of a future solar cycle. The space radiations considered are the bursts of protons and alpha particles that are associated with flares on the solar disk (solar flare radiations). Radiations of galactic origin as well as those associated with the Van Allen Belt are not considered because of their relatively small contributions to the mission dose. It is assumed that the solar flare environment encountered is that occurring at about 1 a.u., although it is realized[3] that the varying solar distance on interplanetary trips could modify this environment.

For the passive shielding case, it is assumed that the astronauts are shielded by a spherical aluminum shield (although this particular material is far from optimum for shielding). Radiobiological dose from the flares is calculated at two body locations, the skin and the blood-forming organs (BFO). Responses at skin and at BFO depth are each important under certain circumstances; the dose for the skin is calculated at about 0.1 mm below the body's surface, and for the BFO at 4–5 cm below the surface. In calculating the radiobiological dose, production of secondary radiations will (generally) be neglected. It has been shown[4,5] that the dose contributions from secondaries are generally relatively small for shielding thicknesses and flare spectra of interest.

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Space Radiation Environment

Predictions of the space radiation environment associated with solar flare events are, of necessity, based on previous observations of this phenomena. These observations were mainly carried out during the last solar cycle. As time goes by, the level of confidence in these predictions should increase as more and better in situ observations are made by satellites and space probes. Also, at some time in the future, solar phenomena may be sufficiently understood so that meaningful solar radiation "weather forecasts" can be made sufficiently far in advance to affect the planning of long-duration interplanetary missions.

The occurrence of flares, as well as their integrated flux intensities and other spectral characteristics, apparently has random distribution (at least in a given portion of the solar cycle). Questions of which probability distribution functions (for flare occurrence, integrated flux intensity, and other spectral characteristics) are most appropriate for predicting future solar flare environments are quite subjective. The environments postulated by a given investigator are colored by his interpretation of the existing data, and arguments as to the correctness of one model environment as opposed to another are largely nugatory.

To test how sensitive shielding requirements are to the assumed radiation environment, a number of environments (as postulated in recent papers)[6–11] are considered. In utilizing these environments to obtain shielding requirements, a consistent set of ground rules is observed that has the following salient features. 1) Although it has been suggested that the next few solar cycles will probably contain fewer flares than the last solar cycle, it is conservatively assumed that the flare frequency in solar cycle 19 is typical of all others. 2) Time-variations in individual flares are ignored and only the time-integrated characteristics are considered. 3) Particle flux is assumed isotropic. 4) No short-term flare prediction capability is assumed.

Observations have shown apparently no correlation between the number and intensity of individual flares during a given period. Therefore, although it is unlikely that the number of flares during the next several solar cycles will exceed that in solar cycle 19, there is a finite probability of the occurrence of a flare more intense than any seen to date. Whether or not one accepts this premise can lead to markedly different shielding requirements, a point that has been mentioned by Modisette et al.[12] Of the environments considered herein,[6–11] Modisette et al,[10] and Snyder[8] assumed that events more intense than any previously observed can conceivably occur. The shielding requirements resulting from this assumption are later found to be generally more severe than those resulting from the assumptions that no events more intense than those previously observed can occur. This latter assumption was made by Webber,[6] Burrell et al.,[7] and Hilberg.[9] Because of the effect on the shielding requirements, the environments typified by the assumptions made in Refs. 8 and 10 will be designated "pessimistic"-type environments, while those typified by Refs. 6, 7, and 9 will be designated "optimistic"-type environments. Reference 11 assumed an environment between these extremes with resulting intermediate shielding requirements.

The space radiation environments of Refs. 6–11 are used to obtain dose vs shielding parameter curves for both passive and PRS systems in the manner described in the next section. A more complete description of how the environments of Refs. 6–11 were adapted for the present study will be found in the extended version of this paper.[13]

Shielding Calculations

Passive Shielding

The radiation environments of Refs. 6–11 were adapted[13] to obtain curves of dose at both skin and BFO depths vs aluminum shield thickness. Such curves were obtained for probabilities of 0.1%, 1%, and 10% of exceeding a given dose on a 1.5 year mission at solar maximum. The curves are presented in Figs. 1a–c for the skin, and Figs. 2a–c for BFO. These figures show that the differences between the results for pessimistic- and optimistic-type environments are most pronounced at low probabilities, e.g., 0.1%. The curves tend to coalesce at higher probabilities, e.g., 10%; an outcome that could be predicted from the nature of the basic assumptions.

Plasma Radiation Shielding

As a consequence of the PRS physics, a positively charged proton will be repelled by the spacecraft if its energy E_0 is less than the spacecraft's potential, V. If its energy is initially greater than V, it will penetrate the shield with an energy $E_1 = E_0 - V$. A particle having an energy just greater than V in free space will be strongly deflected by the electric field, and can only penetrate it if its initial motion is accurately parallel to some electric field line. An estimate of the strength of this effect is that the flux of particles of energy $E_0 > V$ is reduced by the factor $(E_0 - V)/E_0$ in passing through the field. This factor is strictly correct for simple geometries and is probably at least representative for more complicated ones. It has the right general trend of emphasizing the deflection or scattering phenomenon for particles with free space energy E_0 just greater than V. When E_0 is much greater than V, the deflection is insignificant, and the factor goes to unity.

If $\phi(E)$ is the differential flux distribution function, the fluxes inside and outside the PRS are related as follows:

$$\begin{aligned} \phi(E_1) &= \phi(E_0)(E_0 - V)/E_0 \\ &= \phi(E_1 + V)\, E_1/(E_1 + V) \end{aligned} \qquad (1)$$

The free space integral spectrum is taken to have the exponential rigidity form given by

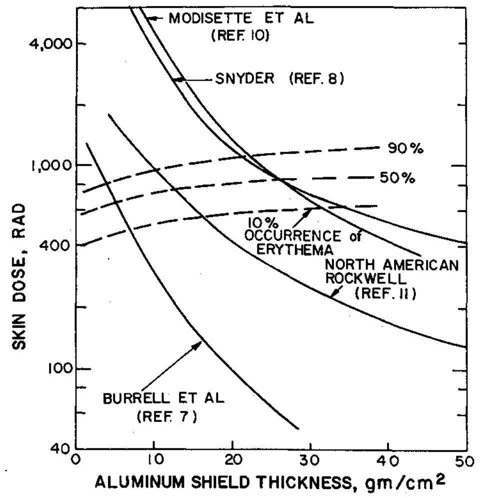
$$F(>E_0) = G \exp[-P(E_0)/P_c] \qquad (2)$$

Then the corresponding differential spectrum in terms of energy is

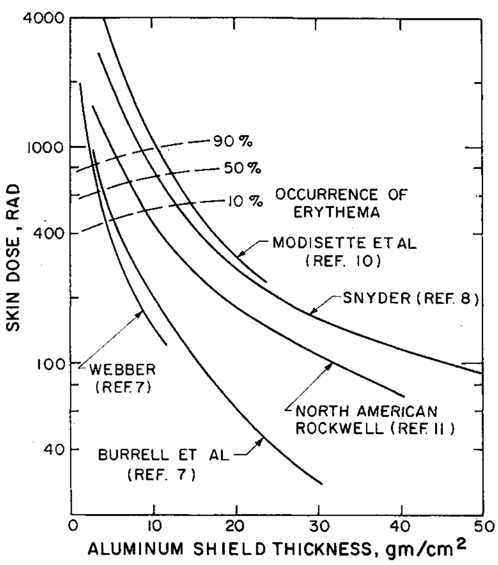
$$\begin{aligned} \phi(E_0) &= (G/P_c\, qK)(E_0 + M) \exp(-K/P_c\, q) \\ K &= (E_0^2 + 2ME_0)^{1/2} \end{aligned} \qquad (3)$$

For a given integral spectrum, as specified by values of G and P_c in Eq. (2), Eqs. (1) and (3) may be used to obtain the differential spectrum inside the PRS with a given voltage V. Use of a suitable flux-to-dose conversion then allows computation of the dose absorbed by the astronauts inside the PRS (in carrying out the calculations described below, a conversion factor was selected that gave dose results for the solid shielding case that agreed with those of Webber[6] and Burrell[9]). This computational procedure was used to generate curves of dose vs PRS voltage with probability of exceeding a given dose as a parameter. These curves were obtained for representative pessimistic and optimistic solar flare environments which were evolved as follows.

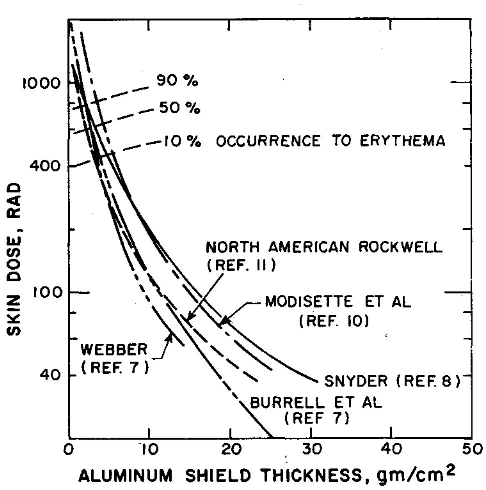
The model environment of Modisette et al.[10] was selected as being typical of the pessimistic-type solar flare environment. This reference assumes that the spectrum of a typical flare can be represented by Eq. (2) with P_c = 97 Mv. A value of integrated flux of 10^9 protons/cm^2 above 30 Mev was arbitrarily selected (being a typical value for a large event), and the computational procedure described above was used to obtain curves of skin and BFO dose vs PRS voltage for this typical flare. Figure 3b of Ref. 10 presents information relating mission-integrated flux to probability of encountering a given flux for the 1.5 year mission. Since the characteristic rigidity is assumed constant, the mission-integrated dose is proportional to the mission-integrated flux. Thus the relations between dose and voltage, and be-



a) p = 0.1%



b) p = 1%



c) p = 10%

Fig. 1 Skin dose vs aluminum shield thickness required for various probabilities of exceeding a given dose.

tween flux and probability can be combined to yield curves of dose vs voltage with probability of exceeding a given dose as a parameter. Such curves, which are analogous to those in Figs. 1 and 2 for the passive shielding case, are shown in Figs. 3 and 4. (It might be noted that the BFO dose curves in Fig. 4 are slightly concave downward. This seemingly anomalous behavior can be explained by the choice of abscissa; if voltage is converted into equivalent solid shield thickness, the curves will take the familiar concave-upward form.)

The model environment of Hilberg[9] was selected as being representative of the optimistic-type solar flare environment; the typical solar flare event assumed in this reference had characteristics similar to the February 23, 1956 flare. It is assumed that the spectrum of this event can be adequately represented by an exponential rigidity type relation [Eq. (2)] with P_c = 195 Mv and $G = 2.83 \times 10^9$ proton/cm². Calculations are then performed, as described above, to obtain curves of dose vs PRS voltage for this event. With the probability of encountering a stated number of solar flare events given by the Poisson distribution, it is possible to obtain curves of dose vs PRS voltage with probability again as a parameter. These curves were generated and, although not shown here, have the same general characteristics as those in Figs. 3 and 4.

Radiobiological Tolerance and Mission Dose Criteria

In order to utilize the curves of dose vs shielding parameter (Figs. 1–4) to obtain shielding requirements, one must specify two additional factors. The first is the maximum permissible dose at the two body sites of interest (the Radiobiological Tolerance Criterion), and the second is the allowable probability of exceeding these dose levels (the Mission Dose Criterion).

It is assumed in the analysis that the total or mission-integrated dose occurs from one large flare (or a sequence of flares in a time period of less than a week). The assumption is not unrealistic since it has been shown[8,10] that during a large number of hypothetical missions, most of the dose results from one large flare. This assumption leads to results that tend to err on the conservative side since fractionation of the dose would allow the body's recovery processes to act and reduce the biological effects.

The ability of the body to recover, at least in part, from sustained radiobiological injury could conceivably be of importance in formulating a radiobiological tolerance criterion. However, the current state of knowledge makes it difficult to quantify this phenomenon with any real assurance. Also, the unknown time-phasing of the flares is another reason that makes it impractical to consider this effect in the analysis.

Although progressive and late somatic damage effects are important under some circumstances, it was felt that the main danger lies with early (i.e., those that occur a few hours to a month after exposure) somatic damage effects. Therefore, the radiobiological tolerance criterion considered only early effects of two types, skin and blood-forming organ damage.

Because of the characteristics of solar flare spectra, when the astronauts are engaged in EVA or behind only a thin

Table 1 Estimated adsorbed dose required to produce erythema[14]

Probability of response	Dose, rad
10%	400
50%	575
90%	750

shield, a large proportion of the incident radiation is absorbed at or near the body's surface, i.e., the skin. Under suitable conditions, a sunburn-like reaction known as erythema will occur in a few hours to a few days after exposure. Larger doses will increase the severity of the erythema and result in other syndromes that are reminiscent of severe sunburns. The rubbing of the spacesuit against the affected areas will cause reactions that are at best annoying and at worst painful. In any case, the reaction will adversely affect the crew's efficiency and should be avoided.

The threshold for occurrence of erythema in individuals varies and Table 1 (from p. 247 of Ref. 14) prerents values for absorbed dose of reference radiation to cause erythema in 10, 50, and 90% of the population. The reference radiation is taken to be 200 to 250 kvp x rays with a mean linear energy transfer (LET) of about 3.5 kev/μ, corresponding to a QF of one. The site of interest for this dose is taken as 0.1 mm below the surface, and the skin area exposed is 35 to 100 cm^2.

The more energetic components of the solar flare spectra will penetrate a considerable distance into the body, even when it is protected by substantial shielding. Of particular importance is the absorption of these radiations by the BFO located on an average of 4 or 5 cm below the body's surface. The consequent damage is manifested by changes in the peripheral blood counts within 1 to 10 days after exposure. Although it is difficult to relate hematological changes to specifics of mission performance degradation, it is generally agreed that a near-normal blood profile, as measured by the peripheral blood counts, must be maintained to ensure reliable performance of duties.

Some of the blood-circulating elements most sensitive to radiation are the platelets. The values of absorbed dose of reference radiation at 5 cm depth that are required to depress the platelet count by 25%, 50%, and 75% are given in Table 2 (from p. 249 of Ref. 14). The significance of these values for a space mission can be interpreted from the following[14] " . . . a 25% depression of circulating blood elements is indicative of early radiation damage to the blood-forming system. A depression of 75% and greater must be avoided, as it approaches the dosage range of probability of early radiation lethality."

As discussed in Ref. 13, the dose values in Tables 1 and 2 are in reasonably good agreement with similar values presented by other authors. One may conclude, that for the skin response, for instance, an acute dose of 400 rad is probably tolerable while a dose of 750 rad is to be avoided. Also, for the BFO response, a dose of 50 rad is probably tolerable while a dose of 250 rad is not.

Values of limiting dose given in Tables 1 and 2 cannot be applied directly to Figs. 1–4 to obtain shielding requirements since several factors that modify the dose-response relationship must first be considered. Discussion of these factors and the formulation of the problem is based on the exposition in Chapter 8 of Ref. 14.

The dose-response relations typified by the values in Tables 1 and 2 are given in terms of absorbed dose of reference radiation under certain reference conditions. For radiations and conditions other than reference, such as in space exposures, certain multiplying factors must be applied. In the nomenclature of Ref. 14, this can be expressed as

$$\text{RES(reu)} = D(\text{rads}) \times QF(f_1 \times f_2 \times \ldots f_n) \qquad (4)$$

Table 2 Estimated absorbed dose required to depress platelet count[14]

Reduction from normal	Dose, rad
25%	50
50%	120
75%	250

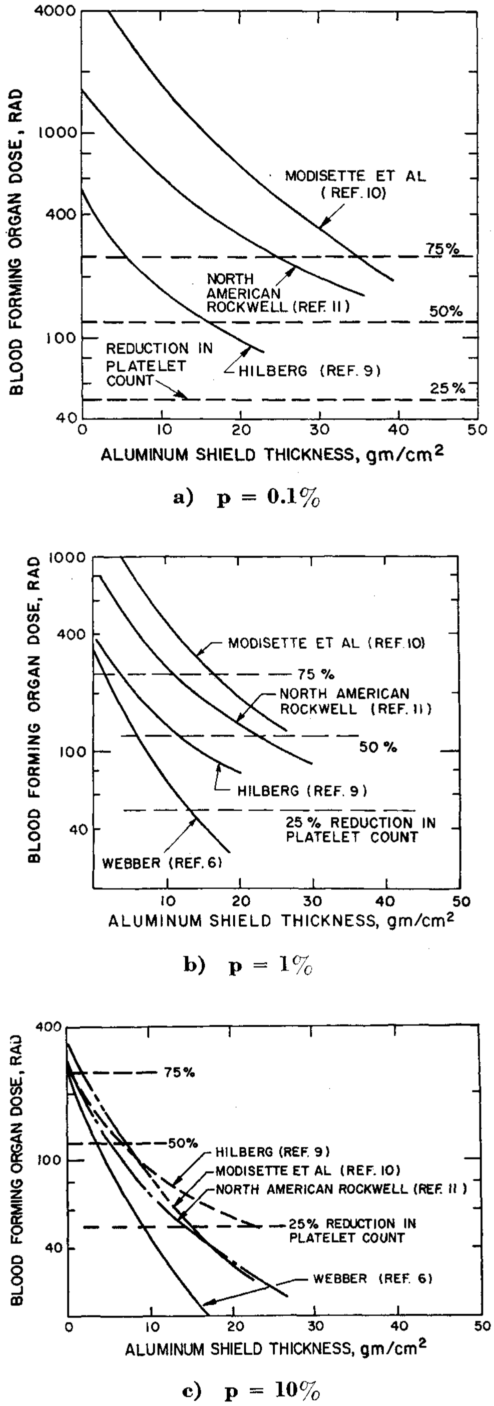


Fig. 2 Blood-forming organ dose vs aluminum shield thickness required for various probabilities of exceeding a given dose.

where RES is the reference equivalent space exposure, reu are reference equivalent units, QF accounts for differences in LET-dependence or radiation quality between the reference and space radiations, and $f_1, f_2, \ldots, f_n$ are factors that account for differences in space and reference exposure conditions. It might be noted that in an earlier notation, dose equivalent was analogous to RES, rem to reu, and RBE to QF. Application of Eq. (4) is as follows: a certain dose D of space radiations is absorbed at the site of interest under given space exposure conditions. Appropriate values of $QF, f_1, f_2, \ldots, f_n$ are used in Eq. (4) to calculate RES. Assuming 1 reu is equivalent in biological risk to 1 rad of reference radiation, the resulting RES value is used to determine the biological response from Tables 1 and 2.

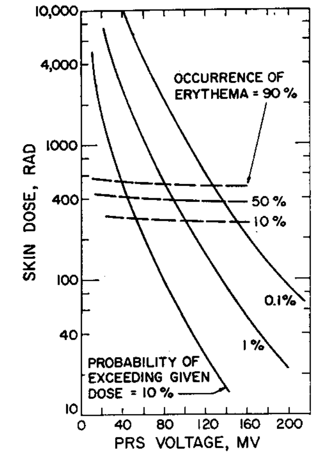


Fig. 3 Skin dose vs PRS voltage required for various probabilities of exceeding a given dose ... "pessimistic" environment.

For a given response to a given type of monoenergetic radiation, QF depends (in general) on the LET value, which in turn is a function of the energy of this radiation. The case of interest here, however, is the spectrum of energies that exist inside the spacecraft at the time of a solar flare. In this case, the effective QF is some function of the interior energy spectrum, which, in turn, depends on the amount and type of shielding. Therefore, the average or effective QF is some function of the shielding parameters. As pointed out in Ref. 14, QF values also depend on whether early or late effects are being considered. For early skin responses, Table 5 of Ref. 14 suggests the following QF values for monoenergetic radiations:

$$\text{low LET } (\leq 3.5 \text{ kev}/\mu),\ QF = 1$$

$$\text{high LET } (>3.5 \text{ kev}/\mu),\ QF = 3$$

For protons, LET $= 3.5$ kev/μ corresponds to a proton energy of about 10 Mev.[15]

For a given solar flare spectrum, transport calculations can be used to obtain the spectrum inside a stipulated thickness of aluminum or PRS voltage. The conditions that $QF = 1$ for energies greater than or equal to 10 Mev and $QF = 3$ for energies less than 10 Mev can then be used to calculate an average QF. This was done for a spectrum that had a characteristic rigidity of 100 Mv (a value close to the mean value of 97 Mv for solar cycle 19 flares[10]), and for various thicknesses of aluminum and PRS voltages. Results in terms of average QF vs aluminum shield thickness and PRS voltage are shown in Fig. 5.

For the case of early hematological response, the same reference recommends use of $QF = 1$, independent of LET value (and therefore independent of shield thickness or voltage).

The other factors in Eq. (4), $f_1, f_2, \ldots, f_n$, account for differences between space and reference exposure conditions.

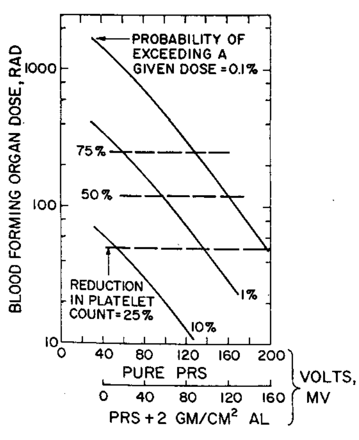


Fig. 4 Blood-forming organ dose vs PRS voltage required for various probabilities of exceeding a given dose ... "pessimistic" environment.

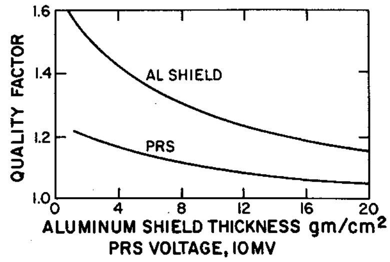


Fig. 5 Quality factor vs amount of shielding, 100 Mv rigidity spectrum; $QF = 1$ for LET ≤ 3.5 kev/μ, $QF = 3$ for LET > 3.5 kev/μ.

For instance, spatial nonuniformities in depth, area, and volume exposed are accounted for by f_p, f_a, and f_v, respectively, and rate effects by f_r. Appropriate values for these factors for early skin and BFO response are discussed in Ref. 13. These values may then be applied to Eq. (4) with the following results: early skin response, $QF = QF(X)$, where, for a 100 Mv spectrum, QF is given in Figs. 5a and 5b (X = shield thickness or PRS voltage) and $f_p = 1$, $f_a = 1.25$, $f_r = 0.5$.

Therefore,

$$(\text{RES})_{\text{skin}} = 0.63 \times QF(X) \times D \tag{5}$$

Early BFO response

$$QF = 1,\ f_p = 1,\ f_v = 1,\ f_r = 1$$

Therefore,

$$(\text{RES})_{\text{BFO}} = D (D \text{ independent of shield thickness or voltage}) \tag{6}$$

The multipliers of D in Eqs. (5) and (6) may be considered as factors by which the ordinate values of the curves in Figs. 1–4 must be multiplied in order to compare the space doses with the allowable reference doses given in Tables 1 and 2. This factor is, of course, unity in Eq. (6) but in Eq. (5) it varies (for passive shielding) from 1.0 at $X = 1$ gm/cm² Al, to 0.72 at $X = 20$, to 0.63 for very large values of X. A similar (but smaller) variation with voltage may be observed for active shielding. Rather than replotting the skin dose curves to account for this variable factor, a simple but less physically-meaningful procedure is adopted of dividing the values in Table 1 by this factor and plotting the results in Figs. 1 and 3. The absorbed doses required to depress the platelet count (from Table 2) are superimposed on the curves of Figs. 2 and 4.

The setting of a Mission Dose Criterion depends on a number of considerations, many of then nontechnical and thus out of the scope of this analysis. However, to utilize the results obtained up to this point, it is necessary to make a judgment on allowable probabilities of exceeding these doses during a mission. For this reason, two approaches leading to two different Mission Dose Criteria are considered.

The first approach is to allow a very low probability of exceeding a dose value that corresponds to significant radiobiological damage. This probability could be made commensurate with that for the occurrence of other comparable spacecraft system failure mechanisms, e.g., the probability of the penetration of the spacecraft wall by a large meteorite. This approach might lead to a criterion of, for instance, 0.1% probability of exceeding 750 rad to the skin or 250 rad to the BFO. (For brevity in the following discussion, this will be designated Criterion A.) The second approach is to allow a higher probability of exceeding a dose level that corresponds to less critical, or even threshold, radiobiological damage. For instance, the resulting criterion might be 10% probability of exceeding 400 rad to the skin and 50 rad to the BFO (Criterion B). This second approach, while leading to generally less stringent shielding requirements than the first, is subject to more uncertainties. For instance, what could be an unimportant response during 95% of the mission time may mean the difference between success and failure if

Table 3 Mission dose criteria

Criterion	Skin damage	BFO damage
A	0.1% prob. of >750 rad	0.1% prob. of >250 rad
B	10% prob. of >400 rad	10% prob. of >50 rad

it occurs during a crucial phase of the flight when the crew members must be possessed of all their faculties. Also, synergistic effects with other space environmental factors may turn a normally acceptable response into an unacceptable response. Both criteria are summarized in Table 3.

Results

Using the Mission Dose Criteria stipulated in Table 3, one can apply these to the results given in Figs. 1–4 to obtain the desired shielding requirements for the passive and PRS cases.

When Criterion A is used in conjunction with Figs. 1a and 2a, and Criterion B with Figs. 1c and 2c, the range of passive shielding requirements shown in Table 4 result. Of a given set of 2 values in Table 4, the first value corresponds to the pessimistic, and the second to the optimistic environment predictions.

Several important conclusions can be drawn from the results of Table 4. First, for the examples chosen, damage to the BFO is more critical than damage to the skin (in that the former requires a greater amount of shielding). This is valid for both criteria when comparing corresponding values for both the pessimistic and optimistic environments. Second, for the pessimistic environments, there is a very large difference in shielding requirements resulting from use of Criterion A as compared to Criterion B. Although this difference is most significant in the case of skin damage, there is also a factor of 2 difference in BFO damage. Because of these large differences, it would seem necessary to give considerable thought in mission planning to the stipulation of the Mission Dose Criterion. For the optimistic environment, this difference is much smaller.

It is of some interest to compare the results that would be obtained if an analogous mission exposure criterion as proposed by the AIAA Spacecraft Technical Committee[16] were used. In this paper, it is suggested that a 1% probability of exceeding 50 rad to the BFO and a 0.1% probability of exceeding 220 rad to the body mid-plane (11 cm depth) be the determining criteria. While the data in this analysis do not allow determination of the shielding requirements on the latter basis, they do on the former basis. Figure 2b then yields a range of from roughly 50 g/cm^2 (Ref. 10) for the pessimistic environment, to 13 g/cm^2 (Ref. 6) for the optimistic environment.

It should be remembered that the shielding thicknesses derived in this section are for an aluminum shield. Considerable weight savings, on the order of 30%–40%, could be attained if a more efficient shielding material, such as polyethylene, were used.

Analogous to Table 4, a similar table can be drawn up to show the range of required PRS voltages. Using the mission radiation exposure criteria previously discussed, together with the curves of Figs. 3, 4, and the similar curves (not shown) for the optimistic environment, Table 5 results.

In Table 5, the first value in each set of 2 corresponds to a pessimistic environment prediction (as given by an analysis similar to that in Ref. 10), and the second to an optimistic environment prediction (as given by an analysis similar to that in Ref. 9). Thus the results for the pessimistic environment in Table 5 are generally comparable to similar values in Table 4, while those for the optimistic environment are not.

As in the case for passive shielding, for the pessimistic environment the requirements on shielding are more severe with Criterion A as opposed to Criterion B. On the other hand, as contrasted to the case for passive shielding, for the pessimistic environment the requirements on shielding to prevent skin and BFO damage are about the same. Also, in Table 5, it is seen that in 3 out of 4 cases the pessimistic environment requires a higher shielding voltage than does the optimistic environment.

Table 4 Ranges of passive shielding requirements

Criterion	Shielding required, g/cm^2 Al Skin damage	 BFO damage
A	22[10]–4[7]	35[10]–6[9]
B	5[10]–3[6]	15[10]–9[6]

Because of the difference in units (g/cm^2 Al and voltage), it is difficult to compare the shielding requirements for passive and active shields from the results given on Tables 4 and 5. While it is true that the voltage of the PRS can be related to the weight of such a system,[2] a comparison based solely on a weight basis would be misleading. Some other factors that must be taken into account in comparing the passive and PRS shielding requirements include: a) differences in shielded volume, use of a PRS permits habitability of the entire spacecraft during a flare while use of a passively-shielded storm cellar restricts the crew to a relatively small volume; b) morphology restrictions, use of a PRS requires a vehicle shape with a hole in the center (e.g., a torus or solenoid) which may be undesirable from other mission considerations; c) reliability, a passive shield is presumably 100% reliable in its operation while any active shielding system is not (no estimates have yet been made of overall PRS system reliability); d) power requirements, use of a PRS requires a substantial source of power with consequent weight, volume, and waste heat radiation problems; and e) supporting technology, optimum use of a PRS requires advances in ancillary technology such as superconducting coils, cryogenic insulation, leak and outgassing control, etc. Thus, the most meaningful comparison of passive and active shielding systems can only be carried out by comparing two spacecraft that each utilize one type of shielding system and are otherwise designed to perform the same mission. It is hoped that such a comparison, which will make use of the shielding requirements data in Tables 4 and 5, will be carried out in the near future.

Some interesting comparisons can, however, be carried out in a simple fashion without the necessity of the spacecraft system comparison discussed above. One way of effecting such a comparison is to note that since a PRS of voltage V in Mv would repel all protons of energy less than V in Mev, the PRS is in a sense "equivalent" to an aluminum shield with thickness that would just stop a proton of this energy. If the pessimistic environment voltages in Table 5 are converted to gm/cm^2 of aluminum on this basis, it is found that these values are substantially lower than their counterpart values in Table 4. The difference is particularly noticeable at the higher voltages. For example, for skin damage and Criterion A, 128 Mv becomes 15 gm/cm^2 Al as compared with 22 gm/cm^2 in Table 4; for BFO damage and Criterion A, 129 Mv becomes 15 gm/cm^2 as compared with 35 gm/cm^2 in Table 4. These differences are probably due to the following two factors. First, for skin damage, the scattering phenomenon discussed in connection with Eq. (1) acts to dispose of a large number of low energy, high LET protons. The scattering, thus, also causes a reduction in average QF for skin damage (see Fig. 5). For BFO damage,

Table 5 Ranges of active (PRS) shielding requirements

Criterion	Shielding required, Mv Skin damage	 BFO damage
A	128–39	129–<20
B	53–37	54–88

the scattering is probably less important in reducing the dose. The enhanced effectiveness of the PRS in this case is probably due to greater efficacy of the PRS against the high energy, deeply-penetrating protons. For example, for a 130 Mev proton, a 100 Mv PRS will reduce its energy to 30 Mev, while an equivalent aluminum shield of 10 gm/cm^2 will reduce its energy to 75 Mev. In this example the proton would not penetrate to BFO depth in the former case, while it would in the latter.

The rate of loss of energy of fast particles in matter is a strongly decreasing function of energy so that a passive shield becomes increasingly less effective as the energy of the incident protons increases. At these energies, a PRS appears superior to a passive shield, as shown in the above example. On the other hand, at low energies, a passive shield is relatively effective. These considerations lead one to examine the possibility of a hybrid shield that would combine the effectiveness of a PRS against high-energy particles with the effectiveness of a passive shield against low-energy particles. Some, if not all, of the passive shielding could be provided by the structural shell of the spacecraft, which typically is about 2 gm/cm^2 aluminum. Thus a hybrid shield that utilizes the vehicle's shell and is equivalent to a 10 gm/cm^2 aluminum passive shield, would require a 60 Mv PRS (located exterior to the shell) to stop a 100 Mev proton. For protons with energies greater than 100 Mev, the hybrid shield is decidedly more effective than the passive shield. For instance, a 130 Mev proton would be slowed to 75 Mev by the 10 gm/cm^2 passive shield. With the 60 Mv, 2 gm/cm^2 "equivalent" hybrid shield, the 130 Mev proton is slowed to 54 Mev. Other examples of hybrid combinations, and comparisons with purely passive systems, may be found in Ref. 2. These comparisons show that hybrid systems remove more energy from incident protons than do equivalent passive systems. Because of this enhanced efficacy, and because a certain amount of passive shielding is inherent in any spacecraft, the hybrid shielding concept appears very attractive and warrants further investigation.

One general conclusion that may be drawn from the investigation is that the role of judgment in determining the necessary amounts of radiation shielding should not be undersold. This factor is of considerable importance in postulating the radiation environment that can be expected on future flights, as well as in the setting of allowable somatic damage levels and acceptable probabilities of exceeding these levels.

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