Concluding Remarks

Equations (2–4) have been shown to give some useful insights to single-stage-to-orbit (SSTO) airbreathing launch vehicle (ABLV) behavior. They also provide a consistent framework for optimization and comparisons of performance.[1,2]

The relations have been presented for SSTO, but they can be modified for two- (or multiple-) stage vehicles by replacing V_{leo} with the burnout velocity of the airbreathing stage.

Some of the design inferences made here arose because it was assumed the SSTO ABLV consumed only hydrogen in the airbreathing phase. Whereas this choice of fuel may be mandatory for vehicles whose maximum airbreathing velocity extends to large fractions of orbital velocity (in the supersonic combustion regime), it is possible that higher density hydrocarbons are competitive at lower velocities. Dual fuel combinations might offer some relief to the problem of tank volume growth, and relations such as Eqs. (2–4) can be constructed to account for this variation. Similarly, there are interesting tradeoffs to consider with vehicles that use intrinsic oxidizer in the airbreathing phase, i.e., $\mu_\alpha > 0$.

Our problem is to explore and find the best points in the α–β plane, then to decide whether any of these points represent a real advantage over all-rocket vehicles. There is no doubt that propellant mass fraction can be reduced by airbreathing; however, regarding payload and dry mass fractions, the question is far more complicated[1-4] and beyond the aims of this brief Note.

Acknowledgment

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Large Solar Flare Radiation Shielding Requirements for Manned Interplanetary Missions

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Introduction

As the 21st century approaches, there is an ever-increasing interest in launching manned missions to Mars. A major concern to mission planners is exposure of the flight crews to highly penetrating and damaging space radiations. Beyond the protective covering of the Earth's magnetosphere, the two main sources of these radiations are galactic cosmic rays and solar particle events. Preliminary analyses of potential exposures from galactic cosmic rays (GCR's) were presented elsewhere.[1,2] In this Note, estimates of shielding thicknesses required to protect astronauts on interplanetary missions from the effects of large solar flare events are presented. The calculations use integral proton fluences[3,4] for the February 1956, November 1960, and August 1972 solar particle events as inputs into the NASA Langley Research Center nucleon transport code BRYNTRN.[5] This deterministic computer code transports primary protons and secondary protons and neutrons through any number of layers of target material of arbitrary thickness and composition. Contributions from target nucleus breakup (fragmentation) and recoil are also included. The results for each flare are presented as estimates of dose equivalent [in units of roentgen equivalent man (rem)] to the skin, eye, and bloodforming organs (BFO) behind various thicknesses of aluminum shielding. These results indicate that the February 1956 event was the most penetrating; however, the August 1972 event, the largest ever recorded, could have been mission- or life-threatening for thinly shielded (≤ 5 g/cm^2) spacecraft. Also presented are estimates of the thicknesses of water shielding required to reduce the BFO dose equivalent to currently recommended astronaut exposure limits.[6] These latter results suggest that organic polymers, similar to water, appear to be a much more desirable shielding material than aluminum.

Calculational Methods

The incident solar flare integral spectrum[3,4] for each of the three flare events is transported through the shield materials using the Langley Research Center deterministic nucleon transport code BRYNTRN.[5] This code uses a marching algorithm based on integral equation solutions to the one-dimensional Boltzmann transport equation. In the straight-ahead approximation, which is appropriate for these energetic particles, this integrodifferential equation is written as

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S(E) + \sigma_p(E)\right]\phi_p(x,E) = \sum_j \int_E^\infty f_{pj}(E,E')\phi_j(x,E')\,\mathrm{d}E' \tag{1}$$

for protons. For neutrons, it becomes

$$\left[\frac{\partial}{\partial x} + \sigma_n(E)\right]\phi_n(x,E) = \sum_j \int_E^\infty f_{nj}(E,E')\phi_j(x,E')\,\mathrm{d}E' \tag{2}$$

where $\phi_j(x,E)$ is the type j particle flux/fluence at x with energy E; $S(E)$ is proton stopping power; $\sigma_p(E)$, $\sigma_n(E)$ are proton and neutron total cross sections, respectively; and $f_{ij}(E,E')$ are differential cross sections for elastic and nonelastic processes. Using the detailed solution methods described in Ref. 5, particle fluxes/fluences as a function of depth and energy are computed. In addition to propagating neutrons and protons, contributions from target nuclear fragments and nuclear recoil are also included. The computational algorithm used to calculate these fluences has been verified to within 1% accuracy by comparison with an analytical benchmark solution[7] to Eqs. (1) and (2). Once the particle fluences are known, the energy absorption per gram of material (dose) can be computed from

$$D_j(x, >E) = A_j \int_E^\infty S(E')\phi_j(x,E')\,\mathrm{d}E' \tag{3}$$

and the dose equivalent H from

$$H_j(x, >E) = A_j \int_E^\infty Q_F(E')S(E')\phi_j(x,E')\,dE' \qquad (4)$$

In Eq. (4), Q_F denotes the quality factor, which is a weighting factor relating energy deposited (dose) to biological damage or risk (dose equivalent). In this work, we have used the values for Q_F recommended by the International Commission on Radiological Protection.[8] The conventional (SI) units of dose equivalent are rem (sievert), where

$$1 \text{ rem} = 0.01 \text{ sievert} = 0.01 \text{ J/kg} \qquad (5)$$

At present, no radiation exposure limits have been established for astronauts on exploratory class (interplanetary) missions. Therefore, we have chosen to use the guidelines[6] proposed for Space Station Freedom. These are listed in Table 1. The actual transport calculations were performed for simple slab geometries, which are equivalent to isotropic radiation incidence on spherical shells. This is conservative. A more careful but computationally complex treatment of the human geometry may result in smaller dose estimates.[3] Nevertheless, the current calculations are adequate for comparisons between shield materials and are useful as a conservative estimate of required shielding thicknesses.

Results

Figure 1 displays BFO dose equivalent (in rem), as a function of aluminum shield thickness, for each of the three solar flare events. The aluminum thicknesses are given in units of thickness (cm) and areal density (g/cm^2). The latter are customarily used for relative comparison purposes, since different shield materials with identical areal densities will yield identical shield masses for a given shielded volume, even though their thicknesses differ. The relationship between mass density ρ(g/cm^3), shield thickness t(cm), and areal density is

$$\text{areal density} = \rho t \qquad (6)$$

where p = 2.7 g/cm^3 for aluminum. Table 2 displays the thicknesses of aluminum shielding necessary to reduce the dose equivalents from each flare below the currently recommended limits. Although not displayed in the figures, dose-equivalent curves for skin and eye exposures are qualitatively similar to Fig. 1.

From these results, it is clear that the February 1956 event was the most penetrating. Fortunately, it contained the fewest particles and therefore was least limiting for skin and eye exposures, 1-cm shield thickness being adequate to prevent exceeding any of the skin or eye exposure limits. From Fig. 1, we note that the unshielded BFO dose equivalent received from this flare (62 rem) would not be mission- or life-threatening. However, it is the most difficult to shield against when considering the 30-day limit, which is most appropriate for limiting overall risk to the astronauts from solar flares. For this limit, nearly 9 cm (24 g/cm^2) of aluminum is needed.

Table 1 Ionizing radiation exposure limits for Space Station Freedom astronauts

Exposure interval	Dose equivalent, rem		
	Skin	Eye	Blood-forming organs
30 days	150	100	25
Annual	300	200	50
Career	600	400	100–400[a]

[a]Dependent on gender and age at initial exposure.

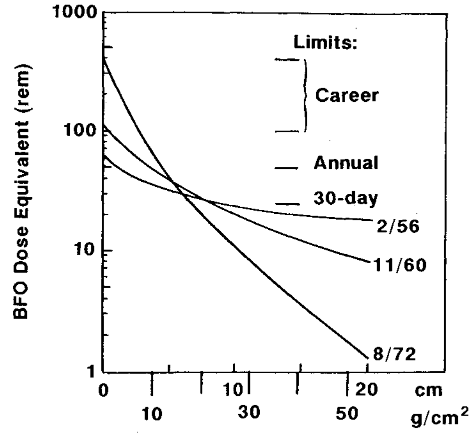

Fig 1 Dose equivalent vs aluminum shield thickness for exposures to the blood-forming organs from three large solar flare events.

For thinly shielded spacecraft (<10 g/cm^2), the August 1972 event was the most limiting. For a spacecraft whose areal density is 2 g/cm^2 (a typical value), 257 rem would be received by the BFO from the flare. Such an acute exposure would likely incapacitate the crew because of radiation sickness and could possibly be lethal. To reduce the estimated dose equivalents below the 30-day skin and eye limits would require approximately 9.5 g/cm^2 (over 3 cm) of aluminum shielding. The BFO dose equivalent for this shield thickness would be 65 rem. This estimated exposure level is larger than either the 30-day or annual BFO limits and would probably induce some physiological changes within an astronaut's body, or increase the probability for latent carcinogenesis, but should not be immediately life threatening. To reduce the estimated BFO dose equivalent below the applicable 30-day limit (25 rem), approximately 18 g/cm^2 (nearly 7 cm) of aluminum shielding is required.

Because the November 1960 solar flare event contained fewer overall protons than the August 1972 event and fewer high-energy protons than the February 1956 event, we would expect that it would not be the limiting event for any of the pertinent exposure limits. Table 2 verifies this.

Finally, the potential usefulness of shielding materials other than aluminum is investigated by computing water shielding thicknesses required to reduce the BFO dose equivalent, for each flare, to the currently recommended limits (Table 1). These estimates are listed in Table 3. Using a water density of $\rho = 1$ g/cm^3, Eq. (6) gives numerically identical results for areal density (g/cm^2) or thickness (cm). Comparing these water shielding thicknesses with the BFO entries in Table 2, it is clear that shield mass savings of 15–30% are possible if water or a similar organic polymer is used instead of aluminum. Since the BFO dose equivalents are the most limiting cases for aluminum, only BFO calculations were performed for water.

Shielding Strategies

Based on these results, it is clear that alternatives to aluminum must be considered for spacecraft shielding applications. The results for water shielding suggest that organic polymers would offer a significant reduction in shield mass for the same level of crew protection. Still, it appears that areal densities of at least 10 g/cm^2 may be necessary to provide adequate protection, irrespective of the material selected. Shield optimization analyses and a proper treatment of the human geometry could further reduce these conservatively estimated shield thicknesses; however, it is likely that the required shielding will continue to be much thicker than for previous manned missions. Rather than shielding the entire spacecraft to these thicknesses, which would involve a substantial weight penalty, consideration should be given to providing a "storm shelter" for the crew to retreat into whenever a large flare occurs.[3] One

Table 2 Aluminum shielding thicknesses required for solar flare protection

	Shield thickness[a]					
	30 days		Annual		Career	
Organ	g/cm²	cm	g/cm²	cm	g/cm²	cm
	February 1956 event					
Skin	1.3	0.5	0.6	0.3	0.3	0.1
Eye	1.5	0.6	0.5	0.2	0.2	0.1
BFO[b]	24	8.9	2.5	1.0	0	0
	November 1960 event					
Skin	2.5	1.0	2.0	0.8	1.0	0.4
Eye	3.5	1.3	2.0	0.8	1.0	0.4
BFO	22.0	8.1	9.0	3.3	1.0	0.4
	August 1972 event					
Skin	7.5	2.8	5.5	2.0	3.0	1.1
Eye	9.5	3.5	6.0	2.2	4.0	1.5
BFO	18.0	6.7	11.5	4.3	7.0	2.6

[a]Rounded to nearest 0.1. [b]Blood-forming organs.

Table 3 Water shielding thicknesses for protection of the blood-forming organs

	Required shield thickness, g/cm² or cm		
Exposure interval	February 1956 event	November 1960 event	August 1972 event
30 day	20	17	15
Annual	1.7	7	10
Career (lower limit)	0	0	1

possible method of implementing this concept would be to provide heavily shielded sleeping quarters in the form of thick cylinders. Such an arrangement would also provide reduced exposures from the continuous background flux of GCR's.

As an alternative to passive bulk material shielding, the use of active shielding methods involving electromagnetic fields to deflect the heavy charged particles (solar flare protons and GCR's) exists. Although potentially feasible for use as a solar flare shield,[9] such a shield configuration would provide no protection from GCR particles, since it would be virtually transparent to them because of their high energies.[10] In addition, unlike material shielding, electromagnetic shielding is not "fail-safe." Finally, we note that combining the two methods through the use of bulk materials for GCR shielding and electromagnetic fields for solar flare shielding is probably useless redundancy, since bulk shielding for GCR particles will probably also provide adequate shielding against solar flares also.

Conclusion

Estimates of radiation exposures resulting from three large solar flare events are presented for manned missions beyond the Earth's magnetosphere. Dose equivalent values for skin, eye, and BFO exposures are presented for each flare as a function of aluminum shield thickness. Of the three flares considered, the February 1956 event was the most penetrating. The most limiting, however, was the August 1972 event, which could be mission- or life-threatening because of the large number of particles involved. For this event, typical spacecraft thicknesses of ~2 g/cm² would not protect the crew from potentially lethal exposures. To reduce the estimated dose equivalent for this flare below the applicable 30-day limit of 25 rem for the BFO's would require nearly 7 cm of aluminum. For the November 1960 event, approximately 8 cm of aluminum shielding is required, and for the February 1956 event nearly 9 cm is needed to reduce the estimated BFO dose equivalent below the 30-day limit. If water is substituted for aluminum as a shield material, weight savings of 15–30% appear possible. These findings suggest that consideration be given to structural/shield materials other than aluminum, in particular, organic composites. Finally, alternative shield configurations such as "storm cellars," or the use of active shielding with electromagnetic fields were briefly discussed. For the latter, it was noted that little or no protection for the crew from GCR's would be afforded by using magnetic fields to shield against solar flare protons.

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