44—The Importance of Space Radiation Shielding Weight

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The shielding weights required to protect astronauts against space radiation should be considered in relation to the weights of the meteoroid shielding and the life support systems. Comparisons have been carried out for a variety of crew sizes and mission durations.

The radiation shield weights were based upon a 1% probability and were obtained from Webber's data on solar proton events. A mission dose of 100 rad was used as the allowed limit. The doses allowed from solar events were reduced by 45 mrad/day due to galactic radiation and by the amount of radiation expected for two high thrust trips through the earth's trapped radiation belts. In the calculation of the shield weights, the "storm cellar" concept was employed, allotting 50 ft³ per man.

The meteoroid shield weights were based upon the work of Bjork and the NASA-Ames Research Center criterion. The single shield thicknesses calculated were modified to take into account the reduced penetration where two facing sheets with space between them are used as the meteoroid shield. A 1% probability of penetration was assumed in the calculations.

The weights of the life support system are dependent upon the assumptions made regarding the particular subsystems to use for a specific mission. Two systems were used for this comparison. The system selected for the 30-day mission provides for body waste storage rather than reprocessing. Each system assumes a cabin leakage rate of 10 lbs/day and a power penalty weight of 320 lbs/kWe.

INTRODUCTION

Historically, the shield designer has worked under two rather divergent forces. First of all, there is the pressure to design a minimum weight shield which derives from the realities of total weight, power, and costs. At the same time, the shield designer has the pressures of conservatism which evolve from considerations of reliability and crew safety. As a result, the problem is approached in a deliberate and iterative manner.

In the early phases of design, the total radiation protection requirements for the crew are determined. The bookkeeping for these requirements is in the form of thickness or weight. The actual shield weight, which must be included strictly for radiation protection, becomes known progressively as the inherent shielding effectiveness of the vehicle is understood.

The importance of the radiation protection weight, then, is best understood when placed in the context of its relation to other spacecraft necessities. Two systems of particular interest are the meteoroid protection and life support (or ecological) system. These systems not only offer potential weight savings, but are also amenable to weight and volume analysis in the conceptual and preliminary design phases.

For the purposes of this study the spacecraft was assumed to be a cylinder, the length of which was two times the diameter, sized on the basis of 700 ft³ per man internal volume.

LIFE SUPPORT SYSTEMS

Life Support Systems comprise those assemblies of subsystems which provide for atmospheric control, food, and water. They range in degree of closure from essentially open to almost full ecological systems. Of particular importance to the shield designer is the fact that these systems contain substantial amounts of storables for which there is a measure of flexibility in the location of storage.

Several life support systems have been analyzed at S&ID (ref. 1). These were

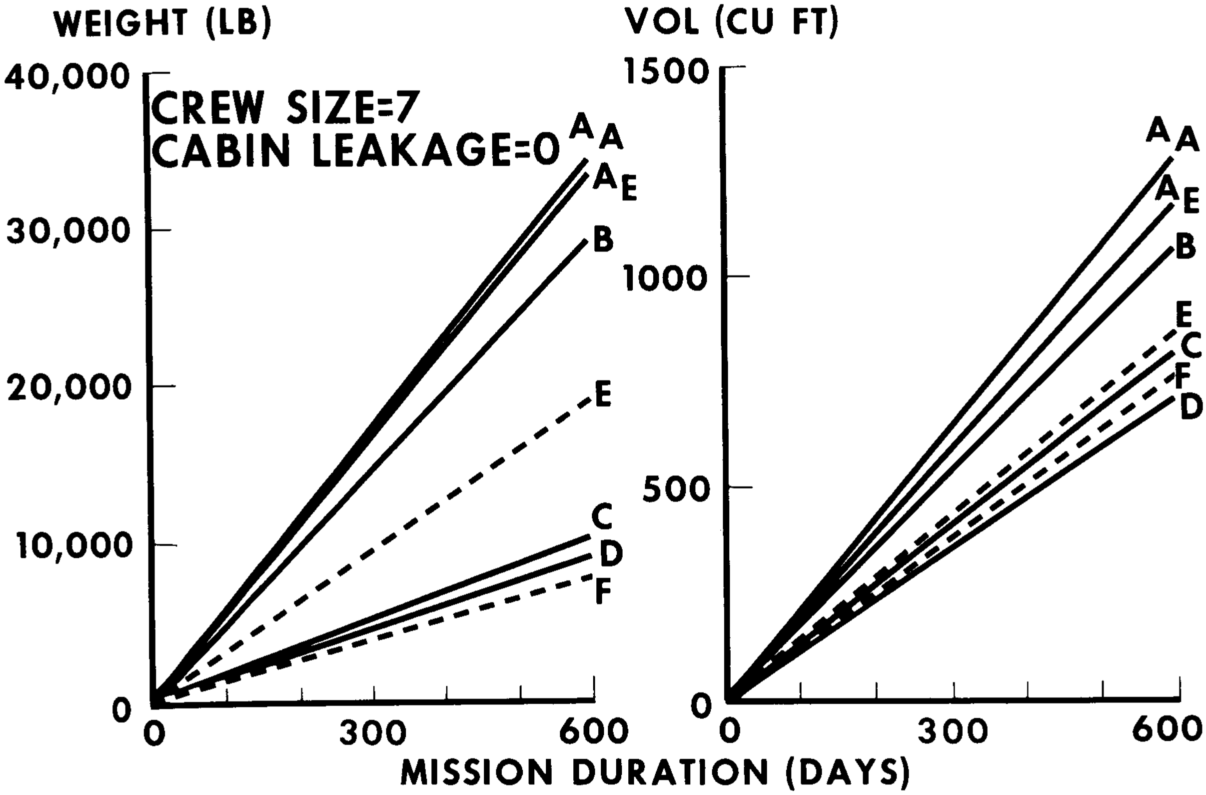

FIGURE 1.—Degree-of-closure results.

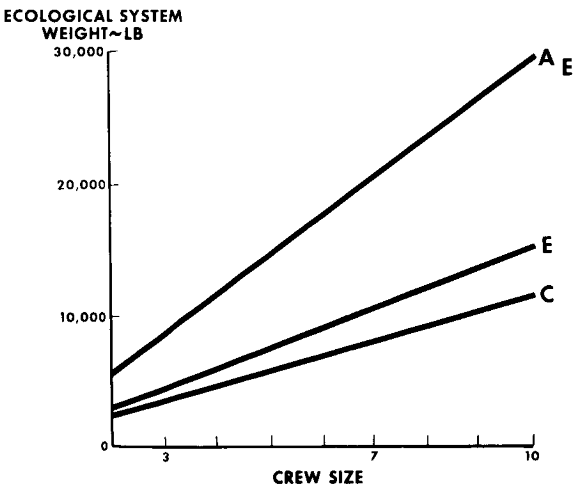

FIGURE 2.—Ecological system weight: 440-day mission; zero leakage.

reviewed during this study for trends in total weight and volume. Table I is a description of the various systems studied. Table II shows their degree of closure and the makeup requirements for each. Systems "A_A" and "A_E" are practical "open" type systems, and the makeup requirements are high. System "C" is considered to be a state-of-the-art closed ecological system and the makeup requirements are down by a factor of 3. Table III shows the weight, power, and volume of the subsystems involved as a function of crew size and mission duration. The subsystems do not combine in a strictly additive manner to make up a system, since ecological balances must be accounted for. Table IV shows the resupply weights and volumes for the various systems. Figure 1 shows the weights and volumes for the various systems as a function of mission duration for a 7-man crew. Figure 2 shows the effect of crew size on the ecological system weight. Here, the mission duration has been fixed at 440 days. In these two figures, it was assumed that there was no cabin leakage, and no power penalty was estimated for externally generated heat loads.

The effects of cabin leakage are shown in figure 3 for three of the systems. Figure 4 shows system weights for two sizes of crews as a

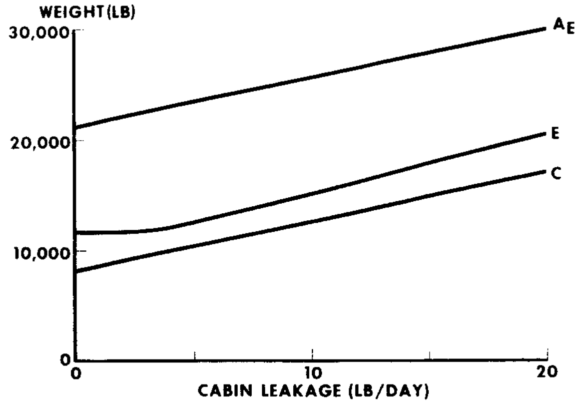

FIGURE 3.—Leakage study results: 440-day mission; 7-man crew.

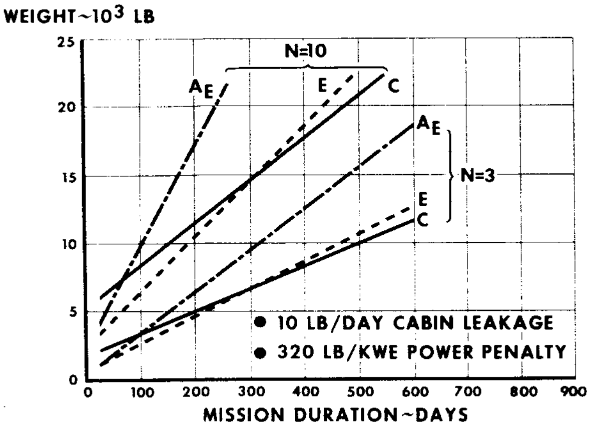

FIGURE 4.—ECS plus power penalty.

function of mission duration assuming a reasonable cabin leakage of 10 lbs/day and a power penalty of 320 lbs/kWe.

METEOROID PROTECTION

Meteoroid protection is of prime importance to the radiation shield designer because it constitutes a mass envelope which is fully effective in radiation protection.

Meteoroids appear to be of two types. The first type has a high density (3–8g/cm³) and is believed to be related to the asteroidal belt which largely lies between Mars and Jupiter. The second type is believed to have a low density ($\lesssim$1 g/cm³) and is believed to be cometary in origin. Both types have velocities lying between 10 km/sec (earth escape velocity) and 70 km/sec (sun escape velocity). Both types have flux distributions which increase as the

TABLE I

Life Support Systems Description

System	Description
A_A Base Point "Open"	(1) Heat rejected by radiators using recycle coolant. (2) CO_2 removal by adsorption. (3) Wash water reclaimed. (4) Materials stored are food, O_2, water, and N_2. (5) Perspiration and respiration water reclaimed.
A_E	Same as System A_A except change (2): (2) CO_2 removal by electrodialysis.
B	System A_E with (6) added: (6) O_2 regenerated by hydrogenation.
C	System B with (7) added: (7) Urine water reclaimed.
D	System C with (8) added: (8) Feces water reclaimed.
E (Alternative to B).	System A_E with (6b) added: (6b) Partial urine water reclamation for water balance.
F (Alternative to D).	System C with (6) changed: (6) O_2 regenerated by direct conversion.
"Closed" ECS.	System D or F with feces and other waste products reconverted to food.

mass decreases, with no mass-velocity correlation being apparent. Both types apparently tend to occur in showers, most of which have annual periodicities. This may be due to the inability of measurements to determine the type of meteoroid encountered.

From a space meteoroid shielding standpoint, the important parameters are the mass and velocity distributions. The measurements, however, do not provide such information directly, and therefore, it must be inferred. Bjork obtained an $m^{-10/9}$ dependence, with a velocity distribution from 15 km/sec ($m<10^{-7}$

TABLE II

ECS Makeup Requirements

[Wash water and vapor reclaimed in all systems: Zero leakage compartment]

Percent closure	System	Subsystems	Makeup lb/man-day			
			Food	Water	Oxygen	Total
68. 5	A_A	CO_2 removed—MOL sieve	1. 4	2. 33	1. 80	5. 53
68	A_E	CO_2 removed—electrodialysis	1. 4	2. 90	1. 30	5. 60
73	B	Reduce CO_2 methanation; Produce O_2 H_2O electrolysis	1. 4	3. 34	0	4. 74
84	E	Reclaim urine	1. 4	0	1. 30	2. 70
90	C	Reclaim urine	1. 4	0. 35	0	1. 75
91	D	Reclaim fecal water	1. 4	0. 13	0	1. 53
92	F	O_2 from direct reduction CO_2	1. 4	0	0	1. 40

gm) to 28 km/sec (m>3×10^{-2} gm) (ref. 2). By using this meteoroid environment and the laboratory data available from impact studies, the thickness of aluminum or steel required to prevent puncture by a projectile of the same material was obtained.

Other studies have been carried out along similar lines by Whipple (ref. 3), Opik (ref. 4), and Eickellerger and Gehring (ref. 5). While the theoretical approaches were different, the results predicted are quite similar. Perhaps the most widely used information is the NASA-Ames Research Center criterion. This criterion is discussed in relation to the other studies in a Bellcom report, "The Meteoroid Environment for Project Apollo" (ref. 6). The result is:

$$t^3N=2\times10^{-17} \qquad (1)$$

where:

t=meteoroid shield thickness, m
N=meteoroid flux, meteoroids/m^2-sec

Another relationship required is:

$$P=NE \qquad (2)$$

where:

N=exposure, m^2-sec
$E=AT$

where:

A=area of spacecraft surface, m^2
T=duration of exposure in space, sec

TABLE III

Subsystem Weight, Power, and Volume

Subsystem	Weight lb [1]	Power [1] watts	Heat load, q [1] Btu/hr	Volume[1] Cu Ft
1. Temperature control	$8.07N+0.0091q+43$	30N	102.5N	0.113N
2. CO_2 removal				
2a. Molecular sieve	$0.111N\tau+26.33N+17$	97N	331N	$0.0222N\tau+1.125N$
2b. Electrodialysis	91.0N+27.75	160N	60.3N	0.444N
3. CO_2 reduction				
3a. Electrolysis+methanation.	77.65N	340N	390N	1.0N
3b. Direct CO_2 conversion	10N	182.6N	345N	1.0N
4. Wash water reclamation	$0.107N\tau+10$	3.983N	13.6N	0.128N+0.10
5. Urine reclamation	$0.2356N\tau+25$	5.0N	17.1N	0.051N+0.10
6. Urine sources container	$0.32N\tau$			$0.0513N\tau$
7. Feces water recovery	$0.02356N\tau+2.5$	6.48N	22.1N	0.0032N+0.01
8. Waste storage container	$0.033N\tau$			$0.0066N\tau$
9. Trace contaminant removal	2.4N+4	10N	34.2N	0.5N
10. Personal cleanliness	N+20	2N	6.48N	2.0
11. Ducting and blower	N+10	66N	225.72N	0.044N+0.20
12. Cabin atmosphere	24.71N			(700N)

[1] N=crew size; τ=mission duration, days; q=process heat load, Btu/hr.

Combining equations (1) and (2) yields

$$t=\left[\frac{2\times10^{-17}AT}{P}\right]^{0.33}$$

$$=2.7\times10^{-6}\left(\frac{AT}{P}\right)^{0.33} \quad (3)$$

It is seen that in this form the Ames criterion looks like Bjork's formula

$$t=2.5\times10^{-6}Kv^{0.33}\left(\frac{A\tau}{-\ln p'}\right)^{0.31} \quad (4)$$

where

K=constant=1.64 for Al on AL
=0.908 for steel on steel
v=velocity of meteoroid, km/sec
p'=probability of no hits

Table V shows single and double sheet thicknesses of aluminum meteoroid shielding calculated using Bjork's formulation and the Ames criterion.

RADIATION SHIELDING

Calculating the radiation thickness needed for a mission in space requires some knowledge of the mission profile. If trapped radiation belts around planets with magnetic fields are avoided, the remaining sources of radiation are galactic (cosmic) particles and solar event particles.

To a first approximation, the galactic radiation is constant in time and space, and the dose rate is almost independent of shield thickness (for thicknesses up to a few tens of gm/cm²). The dose rate varies from ~30 mrad/day during periods of maximum solar activity to ~45 mrad/day when the sun is quiet. For purposes of this study, a constant value of 45 mrad/day was used.

The major sources of radiation in space are solar events (flares). Only gross probabilities of flare occurrence can be predicted, as flares tend to occur in 11-year cycles with the most recent minimum in 1964 to 1965. During solar maxima, flares are 5 to 10 times as probable as during solar minima. Unless the actual year in which the mission will take place is specified, one can use the solar cycle average only for estimating the solar event radiation environment. For the purpose of this study, this assumption was made with Webber's tabulation of the 1956 to 1961 data being used as a basis (ref. 7).

TABLE IV

Ecological Systems Atmosphere and Food Resupply Weight and Volume

Item	System	Subsystems—Items from table III	Weight, [a b c] lb	Volume, [a b c] cu ft	Comments
1	A	1, 2, 4, 6, 8, 9, 10, 11, 12	---------	---------	
1a	A_A	Molecular sieve Co_2 removal	6.007$N\tau$	0.208$N\tau$	Molecular sieve 30 day
1b	A_F	Electrodialysis CO_2 removal	6.048$N\tau$	0.048$N\tau$	Resupply
2	B	1, 2b, 3a, 4, 6, 8, 9, 10, 11, 12	5.143$N\tau$	0.196$N\tau$	
3	C	1, 2b, 3a, 4, 5, 8, 9, 10, 12	1.8539$N\tau$	0.1459$N\tau$	
4	D	1, 2b, 3a, 4, 5, 7, partial 8, 9, 10, 11, 12	1.612$N\tau$	0.1425$N\tau$	
5	E	1, 2b, 4, partial 5 & 6, 8, 9, 10, 11, 12	2.860$N\tau$	0.1607$N\tau$	Complete water balance
6	F	1, 2b, 3b, 4, partial 5 & 6, 8, 9, 10, 11, 12	1.47$N\tau$	0.140$N\tau$	Complete oxygen and water balance

[a] N = Crew size, No. men; τ = mission duration, days.
[b] Container and hardware weights and volumes are included.
[c] N_2 and O_2 are stored at 150 psia, subcritical, cryogenic with boil-off equal to usage rate.

TABLE V

Single and Double Sheet Thicknesses of Aluminum Meteoroid Shielding

Crew size	Mission duration, days	Meteoroid protection weight, lb			
		Bjork		Ames Criterion	
		Single	Double	Single	Double
3	30	8500	2380	4038	1130
	100	12 200	3410	6020	1686
	300	17 250	4815	8680	2430
	1000	24 250	6780	12 950	3630
7	30	17 800	5000	8600	2410
	100	25 200	6980	12 840	3600
	300	35 600	10 000	18 500	5200
	1000	51 000	14 400	28 800	8050
10	30	24 300	6780	12 500	3495
	100	35 400	9920	17 650	4940
	300	48 200	13 500	25 500	7120
	1000	69 300	19 400	38 100	10 660

The radiation shield thicknesses were constructed using the probability of encountering an integrated flux as a function of mission duration in conjunction with the calculated point doses within a spherical aluminum shield. Figure 5 shows the probability of encountering a total flux above 30 MeV for mission durations from three months to two years. A summary of the calculated point doses for shield thicknesses of 1 g/cm² and 10 g/cm² (corresponding to proton cut-off energies of 30 MeV and 100 MeV) is shown in figure 6. Straight line fits have been applied to these data. From these two plots the total dose probabilities can

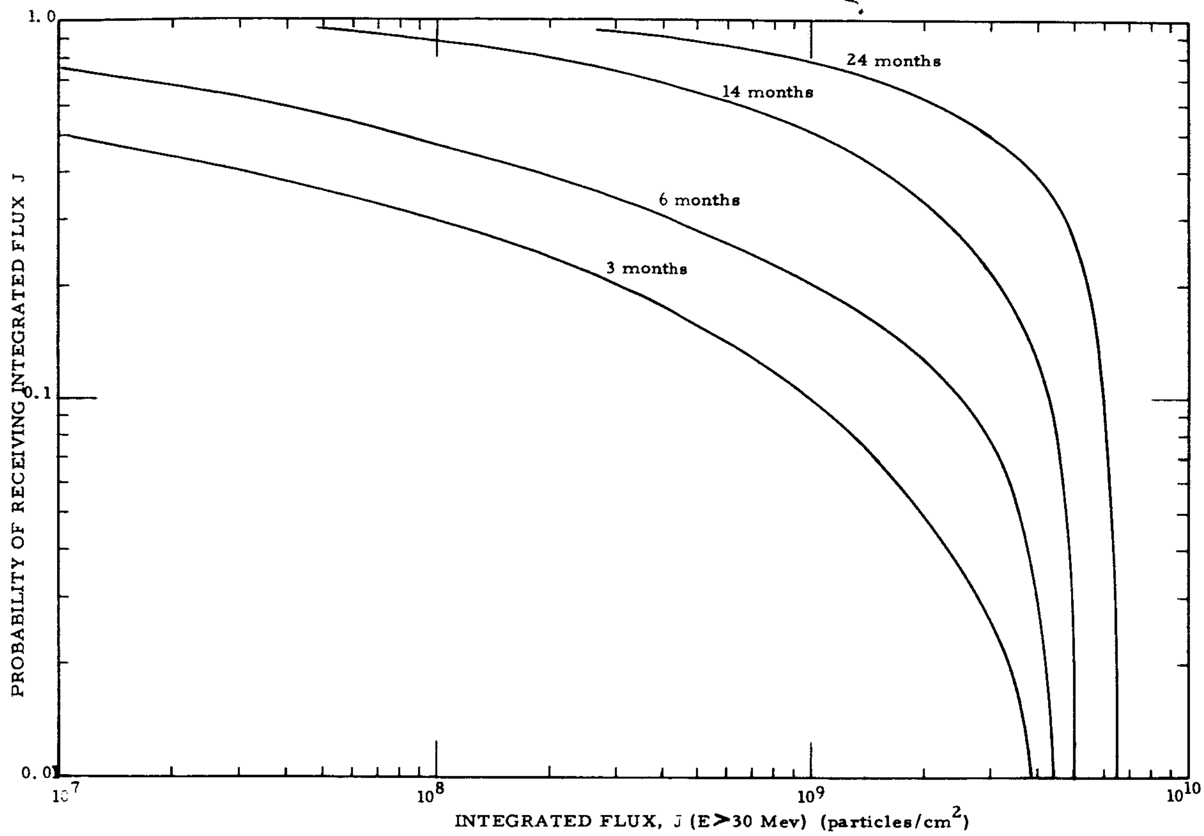

FIGURE 5.—Cumulative probability-flux curves for various mission durations.

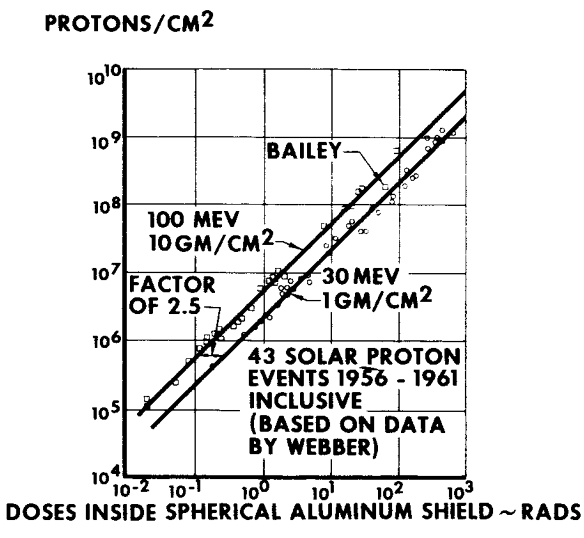

FIGURE 6.—Summary of flare proton flux.

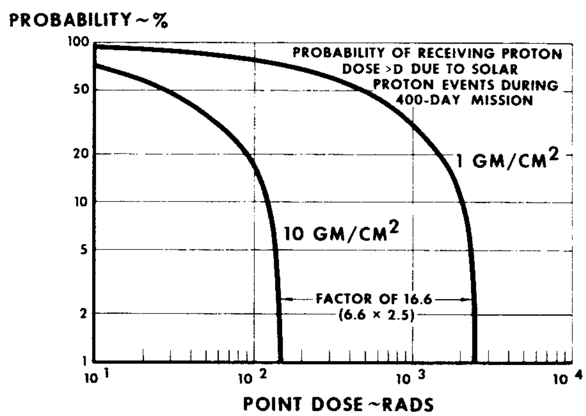

FIGURE 7.—Total dose probability.

be constructed for various mission durations; an example for a 400-day mission is shown in figure 7. Interpolations for other shield thicknesses were made using the dose as a function of shield thickness calculated for the Bailey Model Event, figure 8. Weight calculations were based upon using a minimal volume storm cellar of 50 ft^3 per man. The dose criteria applied was 100 rad/mission to the blood forming organs.

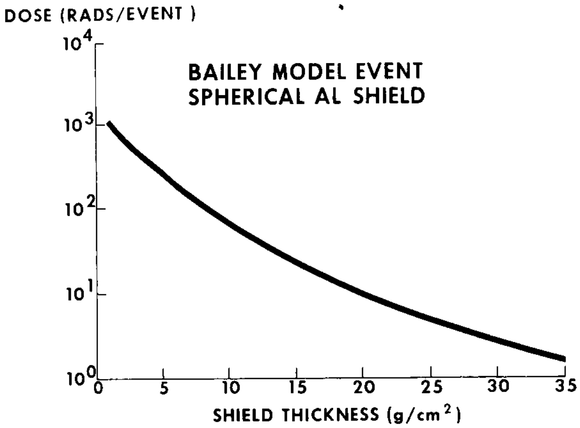

FIGURE 8.—Solar proton integrated dose.

SUMMARY

Table VI shows a summary of the system weights for the life support systems, meteoroid shielding, and the radiation shielding. The radiation shielding weights have been reduced by the protection afforded by the meteoroid protection, but do not include any allowances for the shielding effectiveness of the life support systems. In this regard, it is interesting to note that the resupply needs of system "C" exceed the shielding requirements of a 10-man crew for 300-day missions. While not all these storables can be used as shielding—and there are some consumables included—the advantages and possible weight savings are apparent.

TABLE VI

System Weights

Mission duration, days	Life support system "C"	Meteoroid shielding (Ames Criterion single sheet)	Net radiation shielding (radiation shield–meteoroid shield)
3-Man Crew			
30	1500	4038	1890
100	3300	6020	2200
300	6700	8680	2440
1000	18 200	12 950	2530
7-Man Crew			
30	4100	8600	3100
100	5700	12 840	3520
300	10 600	18 500	3810
1000	27 600	28 800	3520
10-Man Crew			
30	6100	12 500	3530
100	8300	17 650	4190
300	14 500	25 500	4440
1000	36 000	38 100	4180

REFERENCES

1. HONEA, F. I.: Life Support Systems. Manned Mars Landing and Return Mission Study North American Report SID 64–619–3, Sec. 3.1.1
2. BJORK, R. L.: Meteoroids versus Space Vehicles ARS J., June, 1961.
3. WHIPPLE, F. L.: Vistas in Astronautics (Morton Alperin, Marvin Stein, EDS.), Pergamon Press (New York), 1958.
4. OPIK, E. J.: Irish Astronomical Journal, no. 5, 1958, pp. 14; also, Physics of Meteor Flight in the Atmosphere. Interscience, 1958.
5. EICHELBERGER, R. J.; and GEHRING, J. W.: ARS J., Oct. 1962, p. 1583.
6. The Meteoroid Environment for Project Apollo, Annex C, Bellcom Rept., Jan. 31, 1963.
7. WEBBER, W. R.: An Evaluation of the Radiation Hazard Due to Solar-Particle Events. D2–90469, The Boeing Co.
8. HAFFNER, J. W.; and BEEVER, E. R.: Effective Mars Mission Radiation Doses. North American Report SID 64–1298.