N87-17780

RADIATION ENVIRONMENT AND SHIELDING FOR EARLY MANNED MARS MISSIONS

Stephen B. Hall and Michael E. McCann
Marshall Space Flight Center
MSFC, AL 35812

ABSTRACT

The problem of shielding a crew during early manned Mars missions is discussed. Requirements for shielding are presented in the context of current astronaut exposure limits, natural ionizing radiation sources, and shielding inherent in a particular Mars vehicle configuration. An estimated range for shielding weight is presented based on the worst solar flare dose, mission duration, and inherent vehicle shielding.

RADIATION EXPOSURE LIMITS

Dose Limits

The most radiation critical organs are the bone marrow (blood forming tissue), the skin, the lenses of the eyes, and the reproductive organs. Irradiation of these areas can cause delayed effects such as leukemia, skin cancer, cataracts, and sterility/genetic defects respectively. It can also cause shortening of lifespan and an increase in general malignant tumors. High doses over a short time can also cause more immediate medical problems.(1)

Table 1 shows the current radiation exposure limits established for flight crewmen.(2) These limits were established by the Radiation Safety Panel for Manned Spaceflight and represent the total allowable radiation limits for the crew from all sources, including routine medical X-rays. The rationale for adopting these limits, instead of limits used in the nuclear industry, are as follows:

"1. Radiation is only one of many recognized and accepted potential risks that may jeopardize the success of any flight mission.

2. Individual astronauts are carefully selected for their special skills and motivation. The application of existing standards of radiation safety established for large, occupationally exposed groups would unduly limit the ability of this small group of specialists to achieve their objectives.

3. The parameters of some space-radiation risk cannot be precisely predicted; therefore, optimal protective measures will not always be available or even feasible. Since any radiation shielding will add to

4189–86

TABLE 1
RADIATION EXPOSURE LIMITS RECOMMENDED FOR SPACEFLIGHT CREWMEMBERS

CONSTRAINT	BONE MARROW (REM AT 5 CM)	SKIN (REM AT 0.1 MM)	OCULAR LENS (REM AT 3MM)
1–YEAR AVERAGE DAILY DOSE	0.2	0.6	0.3
30–DAY MAXIMUM	25	75	37
QUARTERLY MAXIMUM	34	105	52
YEARLY MAXIMUM	75	225	112
CAREER LIMIT	400	1200	600

the weight of a spacecraft, the reduction in risk to be achieved by the shielding must be balanced against the other uses to which this weight might have been put.

4. Since flight missions may vary in both duration and radiation exposure, the probability and importance of the radiation risk compared with those of other risks must be taken into account for each specific mission. A risk-versus-gain philosophy is most appropriate for this comparison, and the philosophy is particularly useful for evaluation of radiation risk. The latter is generally a cumulative one that should not require an urgent all-or-none type of decision."(3)

Since these limits were defined, many of the underlying tenets have changed. Consequently, the limits are being revised to be more stringent. Since they will not be officially redefined for several months, the limits previously cited are used in this paper.

Radiation Sources

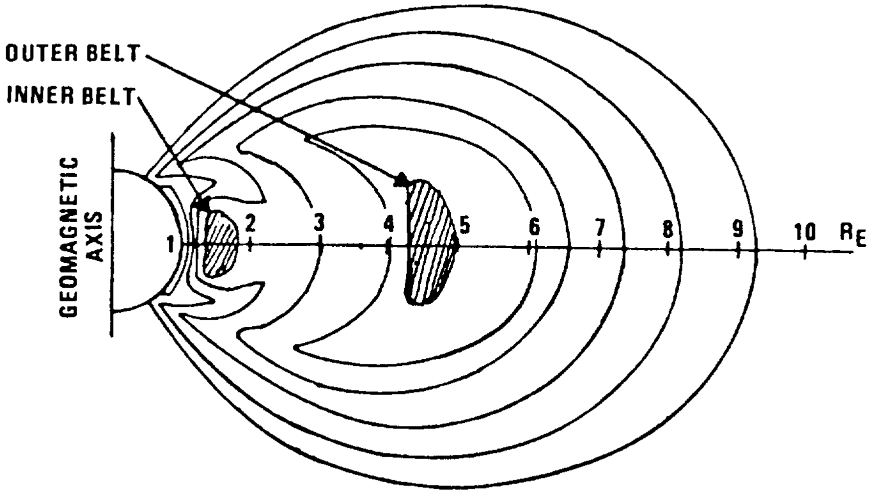
There are three major sources of natural ionizing radiation which the Manned Mars Mission crew will encounter. They are the trapped particles in the Van Allen radiation belts, galactic cosmic rays, and solar flares. In the following sections, each source is discussed with respect to the hazard it poses to a crew.

Van Allen Belts

The Van Allen belts consist of electrons and protons trapped in the geomagnetic field. They are generally described as two somewhat overlapping radiation belts, an inner one comprised predominantly of protons and an outer one comprised primarily of electrons. A simplified diagram of the belts is shown in Figure 1. Doses from the protons are due mainly to primary particles however, the dose from electrons can be far more severe from secondary radiation than from the primary particles. As low energy electrons are absorbed by high-Z materials, they generate x-rays with penetrating power far greater than that of the electrons producing them.(4) Experience from the Apollo flights indicates that the dose from ascending directly through the belts to the moon and returning incurs average mean doses less than .16 to 1.14 rads.(2) Doses, from the terrestrial radiation belts, would probably be comparable for a manned Mars mission.

4188–86

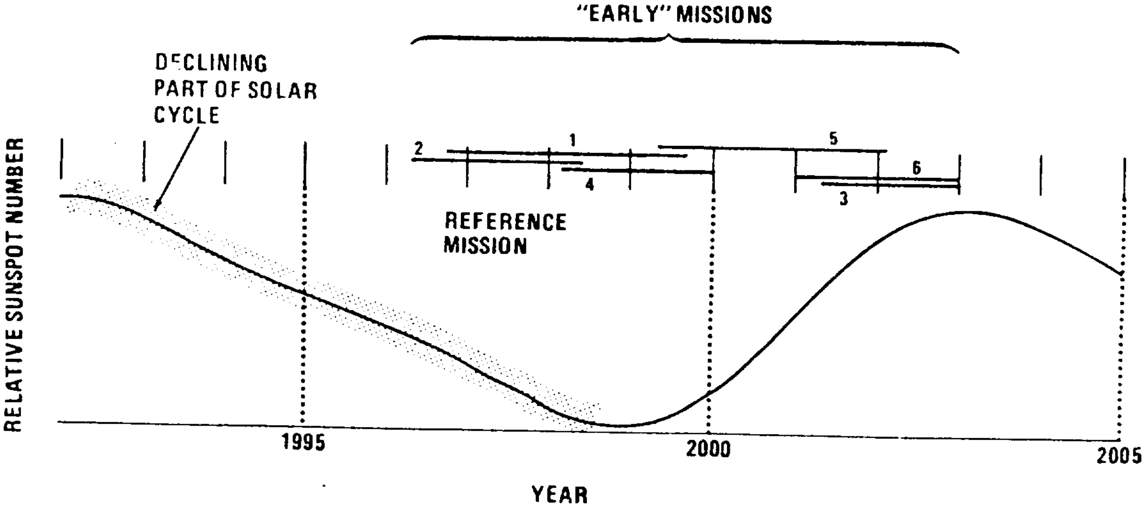
FIGURE 1



VAN ALLEN RADIATION BELTS

3219–85

FIGURE 2.
IDEALIZED SUNSPOT NUMBER VS. TIME FRAME FOR SELECTED MISSIONS



Galactic Cosmic Rays

The second category of radiation encountered by an interplanetary spaceflight crew is galactic radiation. It consists of low intensity, extremely high-energy particles. These particles, 85% protons, 13% alpha particles, and 2% heavier nuclei, bombard the solar system from all directions. The flux levels beyond the influence of earth's magnetic field are relatively constant except during enhanced solar activity when galactic cosmic ray flux decreases. The decrease is caused by an increase in the strength of the interplanetary magnetic field which shields incoming particles.(6) The integrated dose for galactic radiation (without shielding) is 4 to 10 rads/year.(7) No trapped radiation belts, similar to those encircling Earth, have been found around Mars. Therefore, the radiation environment in Martian orbits resembles that in interplanetary space(8) although it is reduced somewhat due to blockage by Mars itself.

Solar Flares

A third significant source of ionizing radiation that may be encountered by the Mars crews is solar cosmic rays or solar flares. A flare is an area on the solar disk where surface temperatures are nearly a thousand times that of surrounding areas. Flares tend to occur more frequently during the declining portion of the eleven year sunspot cycle (Figure 2 shows relationship between sunspot cycle and several mission "windows" in a recent study). Flares always occur in so-called active regions or centers. An active region begins with structural abnormalities in the surface granulation called plages. These plages are followed after a few days by sunspots and those, in turn by flares. Strong active regions sometimes live through several 25-day solar rotations. An active region frequently produces several flares during one passage across the visible side of the Sun, and this is the most important clue for flare prediction. In at least one case during a solar maximum, the same active region produced a second major flare after its second appearance on the visible side.

Large flares are rare events, occurring only a few times during the 4 to 6 year period of high sunspot activity in the 11 year solar cycle. Flares require only a matter of minutes to develop. The optical phenomenon on the Sun usually lasts only 30 to 50 minutes. The emission of electromagnetic radiations from flares is limited to the time of visible activity, but solar protons continue to arrive in the vicinity of the Earth up to 36 or even 48 hours after a flare.

Classifying flare events according to radiation hazards is difficult because no distinct types of flares can be defined. Not only does the total dose for individual flares vary over an extremely wide range from fractions of a rad to doses approaching 1,000 rads, but so do the instantaneous dose rate and spectral configuration at different times during the same event. The time profile of flux buildup and decay and the slope of the energy spectrum for each solar particle changes as the flare event progresses. This greatly complicates calculation of depth-dose distribution and compensation for shielding effects.

Flares from the solar maximum in Cycle 19 have been studied in detail to determine depth-dose distributions behind simplified vehicle-shield systems. The largest events from one study are depicted in Table 2. Due to measuring limitations, the data in this table should be considered representative of the general exposure levels, rather than as exact individual doses. Furthermore, data in the table assumes uniform shield thickness. Actual space systems always show a complex distribution of shield thicknesses covering a wide range. For example, on the Apollo vehicle the range extends from about 1.75 g/cm^2 to 212 g/cm^2. In such systems, the dose distribution throughout the body becomes extremely complex.

Table 2 reveals that 92% of the total dose during solar cycle 19 was delivered in eight critical periods, each of which was 10 days or less, randomly spaced over six years. Additionally, 64% of the total was confined to periods around February 23, 1956; July 10-16, 1959; and November 12-15, 1960.

One method for assessing the flare hazard for humans is to determine the maximum and minimum doses encountered for various launch dates on a mission of a given duration. Table 3 shows just such data for Cycle 19. Notice that the worst dose expected for a week is the same as for two weeks, and a month, and almost the same dose as for several months.(9) This further illustrates the sporadic nature of flares.

4187–86

TABLE 2
TOTAL ESTIMATED SOLAR FLARE DOSES BY EVENT FOR 10 SHIELDING CONFIGURATIONS

DATE	SHIELDING CONFIGURATION									
	1/0[a]	2/0	5/0	10/0	20/0	1/5	2/5	5/5	10/5	20/5
2/23/56	280.00	181.00	91.80	50.20	24.80	64.78	58.00	43.75	30.40	17.90
8/3/56	8.50	5.00	2.20	1.00	0.40	1.39	1.21	0.85	0.53	0.27
1/20/57	122.00	43.50	8.30	1.80	0.30	3.42	2.57	1.23	0.46	0.11
8/29/57	77.00	25.10	4.20	0.80	0.10	1.63	1.20	0.54	0.19	0.04
10/20/57	18.50	10.30	4.10	1.80	0.70	2.53	2.17	1.46	0.88	0.41
3/23/58	148.00	53.60	10.90	2.50	0.40	4.67	3.55	1.75	0.69	0.17
7/7/58	150.00	53.70	10.50	2.30	0.40	4.38	3.30	1.60	0.61	0.15
8/16/58	23.70	8.60	1.80	0.40	0.10	0.75	0.57	0.28	0.11	0.03
8/22/58	45.00	14.90	2.50	0.50	0.10	0.96	0.71	0.32	0.11	0.02
8/26/58	75.00	23.10	3.40	0.50	0.10	1.19	0.85	0.36	0.11	0.02
5/10/59	470.00	211.10	59.30	18.30	4.40	30.18	24.28	13.60	6.70	2.10
7/10/59	420.00	214.00	73.20	27.40	8.40	41.56	34.65	21.76	11.84	4.80
7/14/59	650.00	284.50	75.90	22.30	5.00	37.56	30.00	16.75	7.80	2.50
7/16/59	382.00	194.80	67.20	25.30	7.80	38.30	31.98	20.16	11.03	4.50
9/3/60	13.00	7.20	2.90	1.20	0.50	1.77	1.52	0.10	0.06	0.03
11/12/60	484.00	269.60	105.50	44.90	16.20	64.53	55.12	36.87	21.83	10.05
11/15/60	288.00	151.90	55.90	22.40	7.50	30.04	7.91	18.14	10.33	4.49
11/20/60	17.30	9.50	3.60	1.50	0.05	2.14	1.82	1.20	0.69	0.31
7/12/61	25.70	8.40	1.40	0.30	0.03	0.54	0.40	0.18	0.06	0.01
7/18/61	128.00	64.20	21.60	8.00	2.40	12.16	10.11	6.30	3.39	1.35

a. SHIELDING CONFIGURATIONS ARE GIVEN AS X/Y WHERE X IS THE SHIELDING THICKNESS IN g/cm^2 OF ALUMINUM AND Y IS THE SHIELDING THICKNESS IN g/cm^2 OF TISSUE.

TABLE 3
MAXIMUM AND MINIMUM MISSION DOSES* FOR BEST AND WORST LAUNCH DATES DURING ACTIVE PERIOD OF CYCLE 19

MISSION DURATION	MAXIMUM DOSE (RADS)	MINIMUM DOSE (RADS)
4 YEARS	3492	2439
3 YEARS	3229	974
2 YEARS	2781	526
1.5 YEARS	2415	176
1 YEAR	2110	15
9 MONTHS	1963	2
6 MONTHS	1963	0
3 MONTHS	1962	0
1.5 MONTHS	1492	0
1 MONTH	1452	0
2 WEEKS	1452	0
1 WEEK	1452	0

* SURFACE DOSE INSIDE 1 g/cm^2 UNIFORM ALUMINUM SHIELDING. (LANGHAM, 1967)

SHIELDING REQUIREMENTS

Since any additional weight added to a spacecraft decreases its payload capacity, it is prudent to add as little shielding mass as possible without compromising crew safety. This entails using the vehicle mass as much as possible to provide shielding capability and adding supplementary shielding until it offers sufficient protection. The following sections outline a general approach to bracket the shielding mass requirements for a manned Mars mission.

Baseline Dose Limit

Any calculation of shielding requirements must begin with criteria for the maximum dose limit acceptable for personnel. Revised dose criteria are expected to reduce the permissible dose limits when approved. However, until the astronaut dose limits are revised, we will use the current official limits (see Table 1).

Several mission durations were considered based on various launch opportunities. The candidates for "early" missions are shown in Table 4.(10) To derive a reasonable maximum shielding mass estimate, it was decided to use the mission, from a recent study, which had the longest travel time. Several missions had longer total mission times. However, on those missions, it was felt that: (1) the entire crew would probably be on the surface; and (2) providing protection from solar flares and galactic cosmic rays would be easier on the surface than on orbit because of material available for shelter and more flexible operational strategies. Therefore, a long duration mission with a ~60 day stay time, where part of the crew remains in Mars orbit, imposes the most severe shielding mass penalty. For simplicity, it was assumed that there would be no appreciable additional dose from either a nuclear propulsion system or a nuclear power system. Similarly, doses from routine medical x-rays and doses from medical experiments were not included, although they would be relatively easy to incorporate.

The mission meeting all of the above criteria is the "1997 Double Swingby Mission". The duration of that mission is 738 days (2.02 years).

Residual Acceptable Dose

The portion of the dose absorbed during passage through the radiation belts and from galactic cosmic rays is comparatively easy to estimate. The radiation dose from the Van Allen belts is estimated at

TABLE 4. EARLY MANNED MARS MISSION FLIGHT OPPORTUNITIES (REF 10)

NO.	MISSION NAME	MARS STAY TIME (DA)	TOTAL MISSION TIME (DA/YRS)	EARTH DEPARTURE WINDOW
1.	1997 CONJUNCTION MISSION	385	1025/2.81	OCT 28–NOV 27, 1996
2.	1997 DOUBLE SWINGBY MISSION	60	738/2.02	MAR 24–APR 3, 1996
3.	2001 INBOUND SWINGBY MISSION	60	628/1.72	MAR 12–APR 11, 2001
4.	OUTBOUND VENUS SWINGBY FOR 1999 OPPOSITION OPPORTUNITY	60	668/1.83	JAN 11–FEB 10, 1998
5.	CONJUNCTION CLASS MISSION FOR 1999 OPPOSITION OPPORTUNITY	485	1005/2.75	MAR 12–APR 11, 1999
6.	INBOUND VENUS SWINGBY	60	708/1.94	DEC 22, 2000–JAN 21, 2001

less that 1.14 rem. The dose rate from galactic cosmic rays is estimated to be .165 to .265 rems/day, by considering the biological effectiveness of the galactic radiation.(11,12) The bone marrow dose is the limiting dose in these types of calculations. Since the bone marrow dose is generally less than the skin dose for this mission, the dose contribution over the 2.02 years from these sources is less than 122 to 196 rems. Referring to the acceptable dose limits in Table 1, we see that for a career bone marrow dose (400 rem) the galactic cosmic rays and radiation belt exposures would leave 204 to 278 rem available for solar flare doses. A shielding mass could be estimated from this data, but it would be inadequate because the human responses to radiation are dose rate, as well as total dose dependent. The correct level of shielding can only be estimated if the worst dose for each of the time periods and tissue depths cited in the exposure limits (Table 1) are checked.

Worst Likely Dose

Assuming that Cycle 19 is representative of an unusually active solar cycle, and that its most hazardous flares are typical of the most hazardous flares that would be encountered by a Mars mission crew, we can establish a basis to estimate maximum shielding requirements. The maximum doseage in the most hazardous two year period of Cycle 19 is 2781 rems.(11 & 12) However, according to Table 3, a dose of 1452 rems, over 50% of the total, is encountered during a single one week period! This dose is significantly more hazardous than the total two year dose because of the high dose rate.

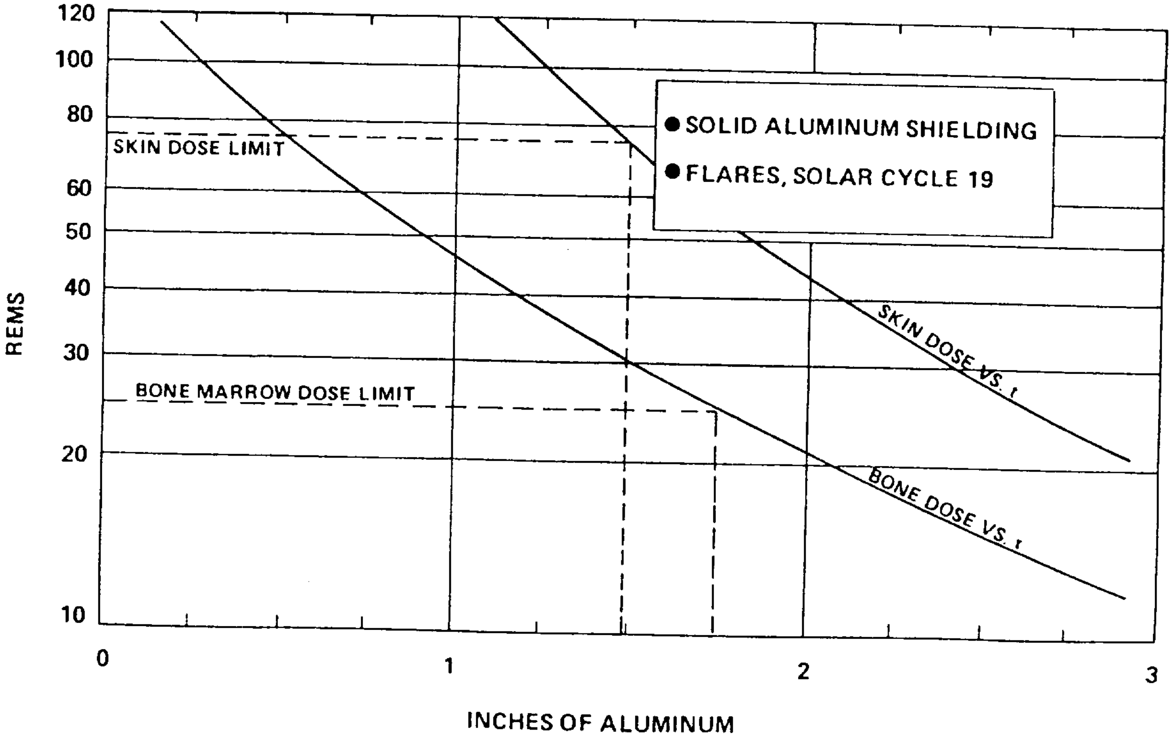
The dose limits in Table 1 show the maximum acceptable dose for a 30-day period (the closest corresponding period) is 25 rem for the bone marrow dose. Figure 3, based on Table 2, shows that for the period cited a uniform shield of aluminum approximately 4.44 cm (1.75 inches) thick would provide sufficient protection. The corresponding thickness based on skin dose limits is also shown to stress the importance of considering all of the dose limits when estimating shielding requirements.

Shielding Mass Required

Given the shielding thickness, the shielding mass can be readily determined if we ignore the shielding effects of vehicle mass and provide a dedicated mass for the shield. Referring to the Celentano criteria for minimum free volume, we allow 1.42 m^3 (50 ft^3/man) for a "storm shelter".

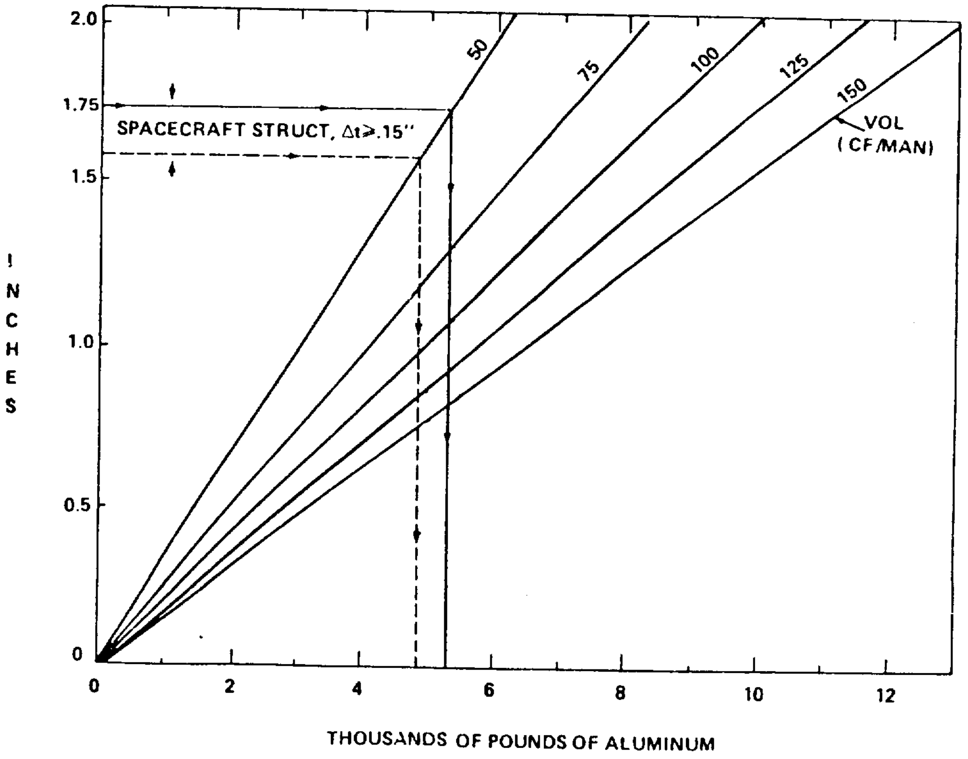
3168–85

FIGURE 3. MAXIMUM 30 DAY FLARE DOSE VS. SHIELD THICKNESS (t)



3489–85

FIGURE 4. RADIATION SHIELDING THICKNESS VS. SHIELDING WEIGHT



This further assumes that the maximum time the shelter would be used is no more than a few days at a time. The crew of six would require 2.82 m^3 (300 ft^3). This corresponds to a spherical enclosure with an inside diameter of 2.52 m (8.3 feet). A sphere that size, fabricated from Al, would weigh about 2430 kilograms (5360 pounds), about 2 1/2 metric tons (see Figure 4).

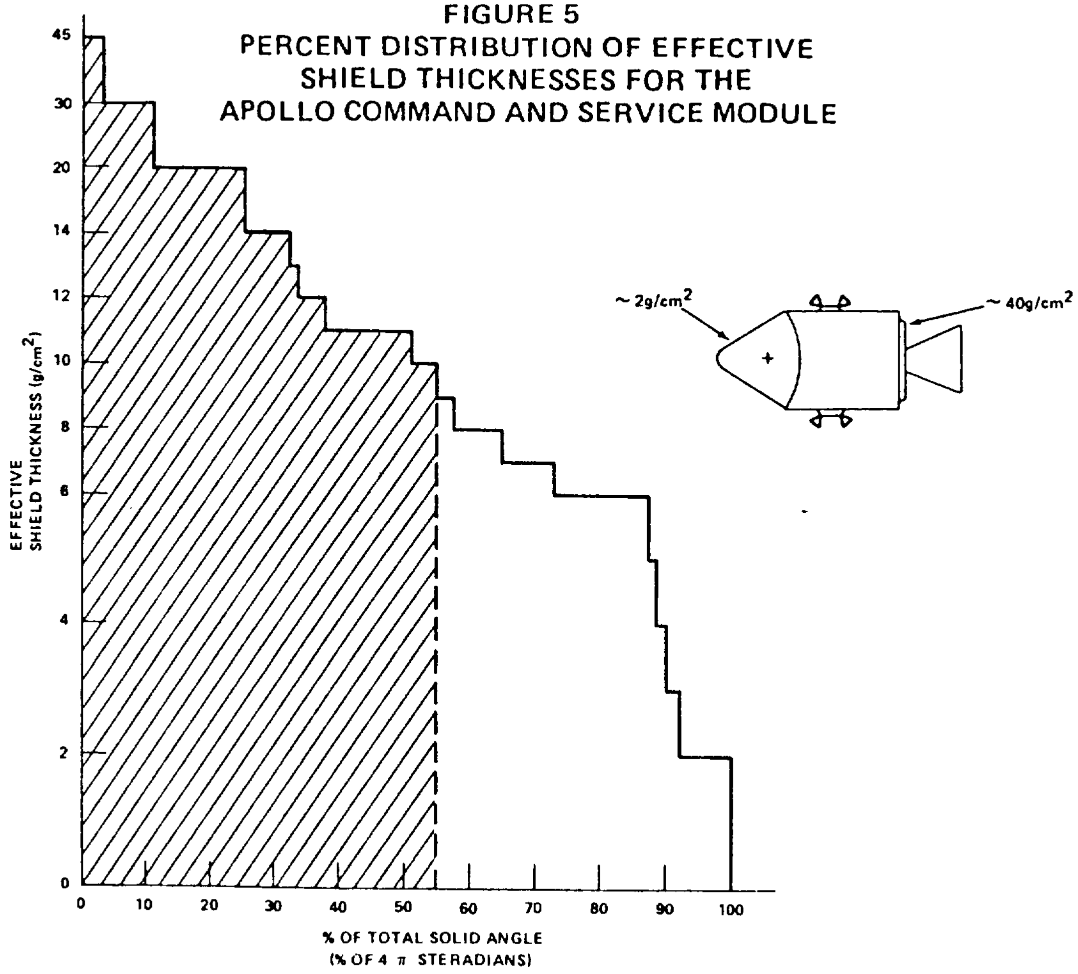
Shielding Available

Past experience indicates that the effective shielding for a typical point inside a spacecraft is considerably higher than would be expected from merely measuring the spacecraft wall thicknesses. For Skylab, the wall thickness was about 1.0 g/cm^2, whereas typical points in the Workshop had effective shielding of approximately 10 to 15 g/cm^2. (13) In the Spacelab module, effective shielding thicknesses ranged from about 1 to over 20 g/cm^2 equivalent aluminum. Figure 5 shows the distribution of equivalent thicknesses for a typical spacecraft. Obviously, the protection afforded by the structure and systems can be significant. It is equally obvious that the magnitude of such shielding cannot be accurately estimated without fairly detailed design concepts.

However, even in early design it is possible to begin estimating the minimum amount of protection that would be provided. This enables the shielding mass to be bracketed and also suggests optimum locations to locate a "storm shelter" for protection from solar flares. The results of such an analysis are depicted in Figures 6, 7, & 8. The first figure indicates the location in the laboratory module that was selected for analysis with an "x". The entire vehicle is depicted here. However, only the shaded portion accompanies the inhabited areas all the way to Mars and back. Consequently, shielding from the first stage, the braking stage, the MEM, and the Mars departure stage are not considered in the analysis. Figure 7 shows the cross section of the lab/logistics module with a detail of the equipment racks. In Figure 8 we see the equivalent thicknesses of material shielding the spot analyzed. The effective shielding thickness graph is drawn in spherical coordinates, with the origin at the point indicated in Figure 6. In Figure 8, we are looking aft along the vehicle centerline. The field of view extends 90 degrees left and right , and 90 degrees above and below the centerline. The shielding levels shown are categorized, the lowest level being .38 cm

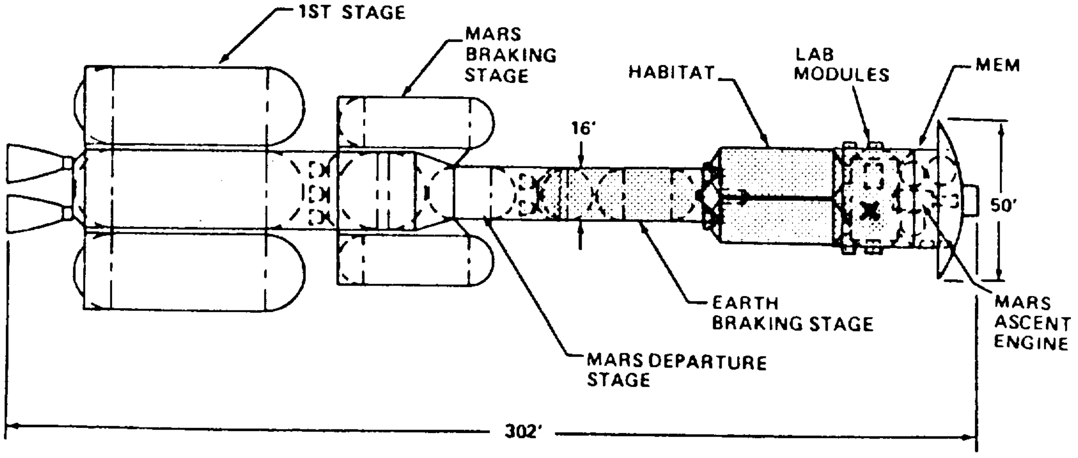
3602–86

FIGURE 5
PERCENT DISTRIBUTION OF EFFECTIVE SHIELD THICKNESSES FOR THE APOLLO COMMAND AND SERVICE MODULE



4186–86

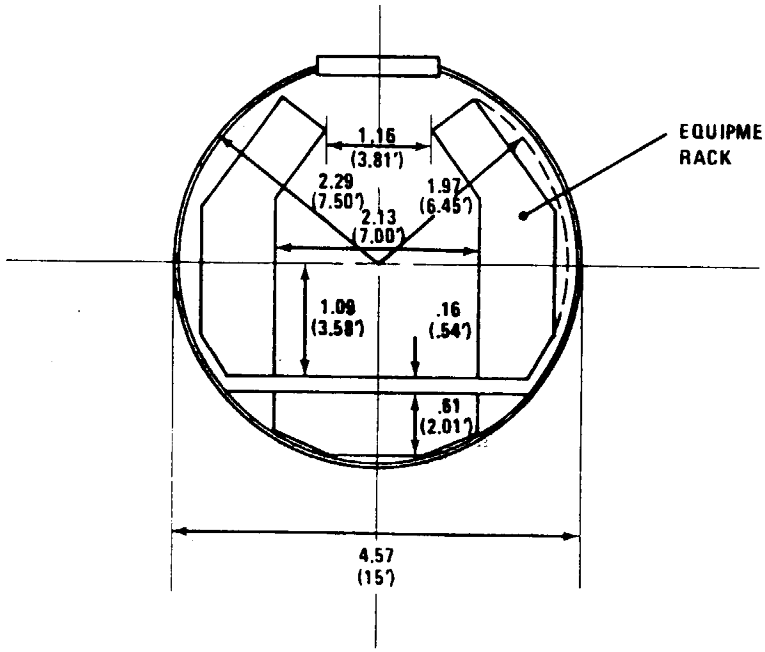
FIGURE 6
MARS MISSION
ALL PROPULSIVE OPTION



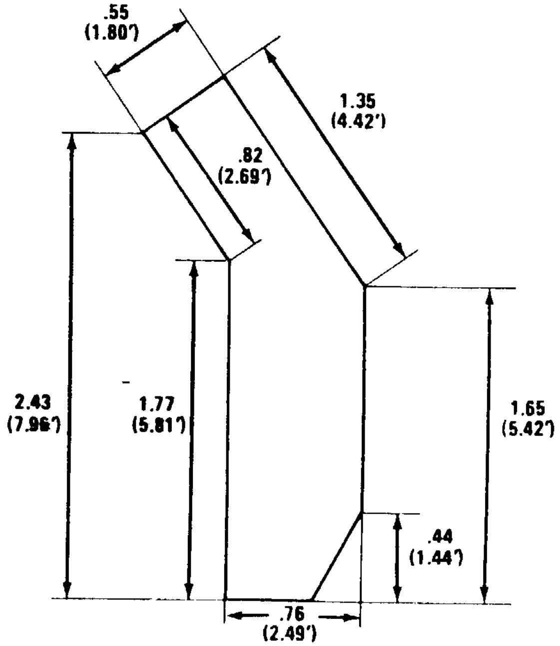
3242–85

FIGURE 7
LAB/LOGISTICS AREA

MODULE CROSS SECTION *



EQUIPMENT RACK DETAIL*



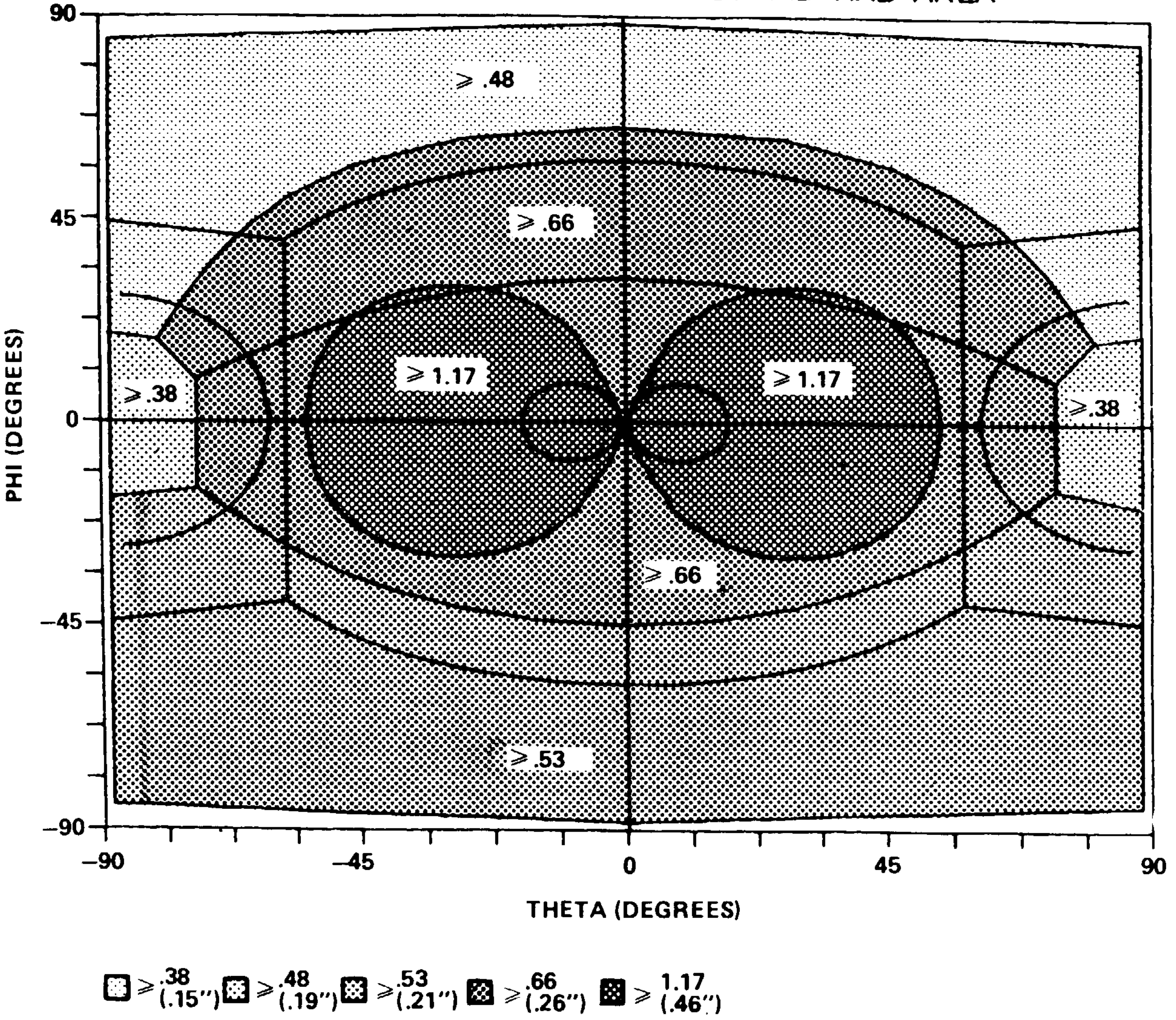
* ALL DIMENSIONS GIVEN IN METERS, WITH ENGLISH UNITS IN (   )

3219–85

FIGURE 8

EFFECTIVE SHIELDING THICKNESS*

LOOKING FROM LAB AREA TOWARD HAB AREA



* THICKNESS GIVEN IN CENTIMETERS, WITH ENGLISH UNITS IN ( ).

(.15 in) or more of aluminum, the next category being .48 cm (.19 in) or more, etc. The least protection is given at the ends of the module where only the .25 cm (.10 in) outer shell plus the .13 cm (.05 in) external support structure is available. The next level is identical except we add .10 cm (.04 in) of overhead locker structure. The .53 cm (.21 in) level is available where we have floor and subfloor structure .15 cm (.06 in) available, instead of the overhead lockers. The thickness is equivalent to .66 cm (.26 in) of aluminum where we have the equipment racks .28 cm (.11 in) in addition to the shell and external support structures. Finally, there is a region where we have the shell of adjacent modules providing shielding. This superimposed .51 cm (.20 in) on the .66 cm (.26 in) previously mentioned, for a total of 1.17 cm (.46 in).

In this simplified analysis, obliqueness of shielding was not taken into account. Also, the equipment racks were assumed to be empty, although they would in reality be nearly full of hardware. These factors would significantly increase the effective thickness of inherent shielding.

To aid conversion among various shielding terms, a nomagraph was prepared relating range (g/cm^2) to equivalent thicknesses in aluminum expressed in centimeters and inches (Figure 9).

Configuration Sensitivity

Vehicle configuration will significantly influence shielding mass and vice-versa. The selection of a site for locating a "storm shelter" for solar flare protection can appreciably reduce mass requirements for the shielding. The analysis done in the current activity suggests that with the configuration shown, the maximum inherent shielding might be available in one of the habitability modules at a site close to the centerline of the vehicle and as far aft as possible.

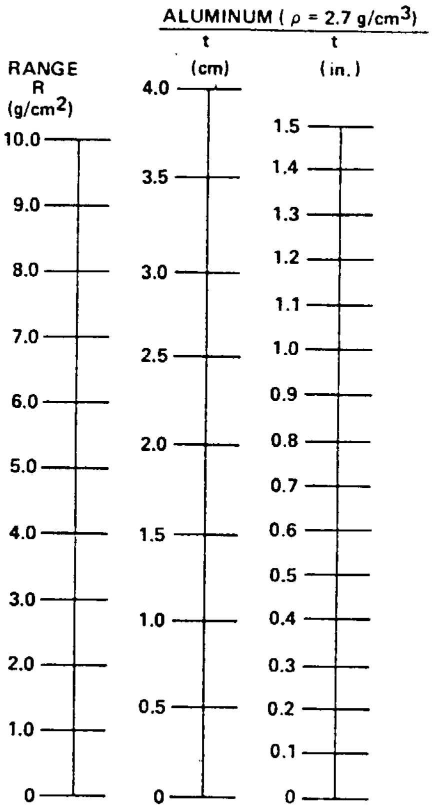
If artificial gravity is provided by spinning the vehicle, it would probably lead to a less compact configuration in which inherent shielding would be more difficult to exploit. In such an instance, it might be feasible to despin the vehicle in response to an impending flare, and reconfigure it to maximize the inherent shielding from vehicle.

Shielding Options

The previous remarks are predicated on using aluminum or an equivalent material for shielding. However, several other materials are at

2549–85

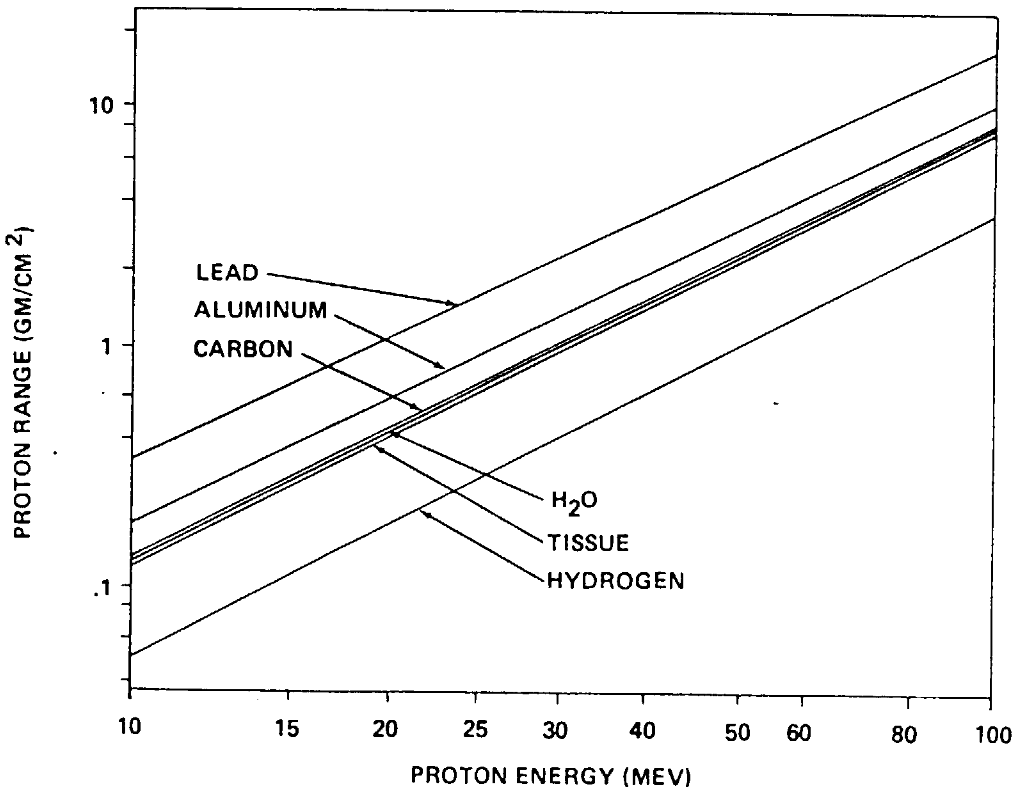
FIGURE 9
CONVERSION SCALES FOR SHIELDING THICKNESS



1.0 IN. = 2.54 cm

3169–85

FIGURE 10
RANGE–ENERGY CURVES FOR PROTONS



least as effective and some are, pound for pound, more effective. Figure 10 shows the relative effectiveness of several examples as well as a few materials that are less effective. Several polymeric hydrocarbons are also good shielding materials because they absorb particles without generating appreciable secondary radiation.

SUMMARY

An approach has been suggested to bracket the range of weight for radiation shielding. The sources of radiation have been described. Precise doseage estimates are difficult to make because of the sporadic nature of solar flares, and because the mechanisms of radiation damage are still under investigation. However, rough estimates of shielding mass can be made. The contribution of vehicle mass to shielding also can be estimated. In further studies of manned Mars missions, the effects of secondary radiation, neutron buildup, and high-Z particles should be fully accounted for as tools are developed to quantify them. Configuration options should be conceptualized that make optimum use of vehicle structure, system, and consumable masses for shielding. Finally, consolidated dose limit criteria and shielding performance data should be developed in consistent, easily interpreted terminology to support future trade studies and design efforts.

REFERENCES

(1) Etherington, Harold; Nuclear Engineering Handbook; New York; McGraw-Hill Co. Inc; 1958; Chapt. 7, pp. 29-31

(2) Nicogossian, Arnauld E. and Parker, James F. ;Space Physiology and Medicine, NASA SP-447; National Aeronautics and Space Administration, 1982; p. 296-297

(3) Langham, Wright H.; Radiobiological Factors in Manned Space Flight, Publication 1487; National Academy of Sciences / National Research Council, Washington, D.C.; 1967; pp. 243-244

(4) ibid., pp 14-15

(5) ibid., pp 18-19

(6) West, G. S., Wright, J. J., and Euler, H. C.; Space and Planetary Environment Criteria Guidelines for Use in Space Vehicle Development, 1977 Revision, NASA TM 78119; National Aeronautics and Space Administration, November 1977; Chapt. 2, pp. 18-19

(7) ibid., Chapt. 1, p. 2

(8) ibid., Chapt. 7, p. 67

(9) Langham, Wright H.; Radiobiological Factors in Manned Space Flight, Publication 1487; National Academy of Sciences / National Research Council, Washington, D.C.; 1967; pp. 20-26

(10) Young, Archie; Mission Concepts and Opportunities; Manned Mars Mission Workshop; June 10-14,1985

(11) Langham, Wright H.; Radiobiological Factors in Manned Space Flight, Publication 1487; National Academy of Sciences / National Research Council, Washington, D.C.; 1967; pp. 9-14

(12) Communications with Stuart Nachtway

(13) Watts, John W., and Wright, J. J.; Charged Particle Radiation Environment for the Spacelab and Other Missions in Low Earth Orbit, NASA TMX-64936; Marshall Space Flight Center, Alabama; 1975, p. 26

(14) Spacelab Payload Accommodation Handbook, ESA Ref. No. SLP/2104; European Space Agency; June 30, 1977; Section 5, p. 47