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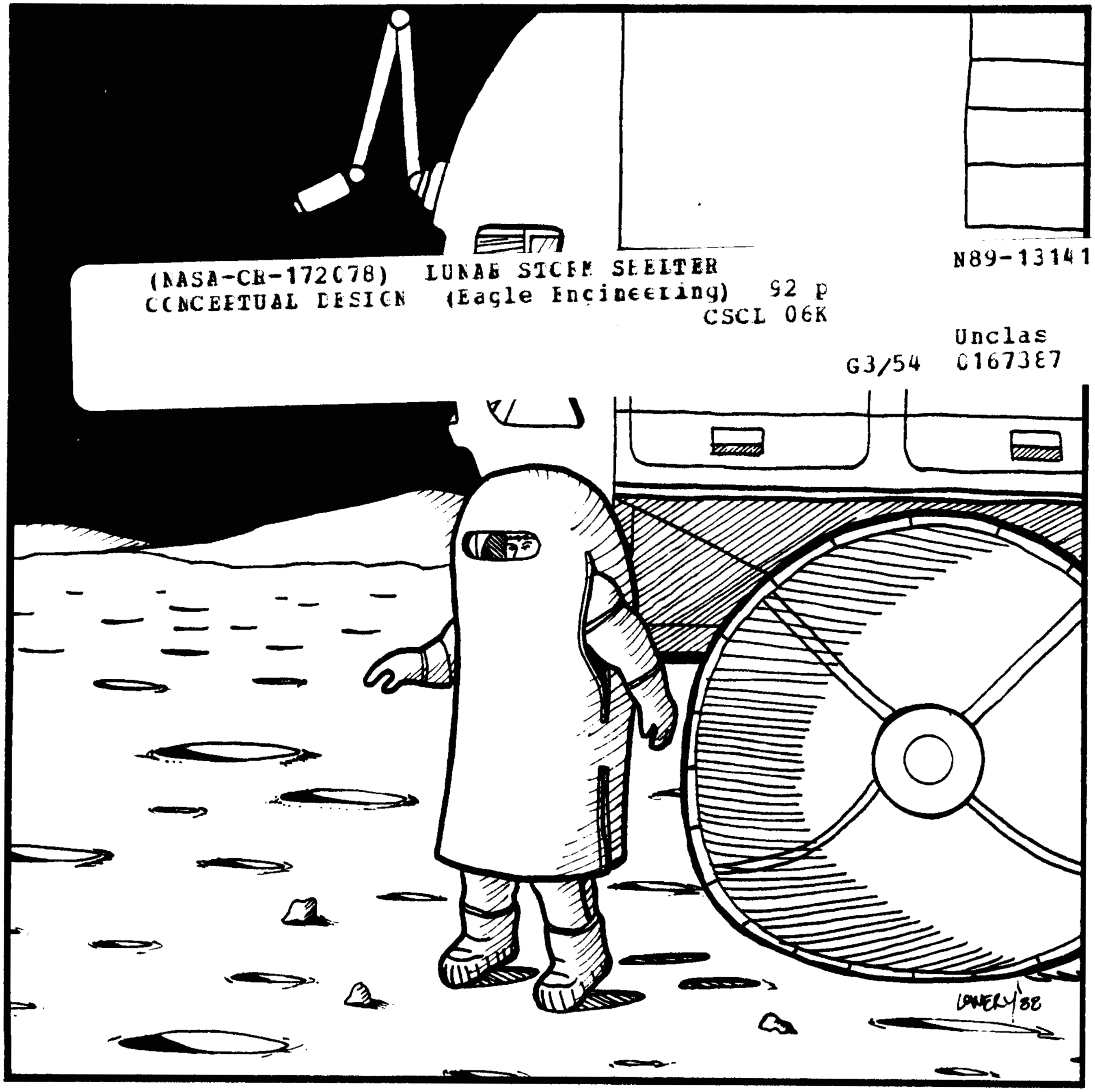
# Lunar Storm Shelter Conceptual Design



NASA Contract Number NAS 9-17878
EEI Report #88-189
May 1, 1988

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# Lunar Storm Shelter Conceptual Design

May 1, 1988

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Advanced Projects Office

Lunar Base Systems Study Task 3.2

Prepared by:
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NASA Contract NAS9-17878
Eagle Engineering Rep. No. 88- 189

# Foreword

This report was prepared during December - April, 1987/88. A series of conceptual designs were produced for lunar shelters for radiation protection. The methods and assumptions behind these designs are documented. This report is a first step in the design process for lunar radiation protection.

Dr. John Alred was the NASA JSC technical monitor for this contract. The NASA task manager was Mr. Mike Roberts.

Mr. Bill Stump was the Eagle Project Manager for the ASTS contract. Mr. Bill Gill was Eagle Task Manager for the Storm Shelter Conceptual Design Task. Other participants included Ms. Carolynn Conley and Mr. Karl Maples.

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## 1.0 EXECUTIVE SUMMARY

Extended occupancy on the lunar surface will require redefinition of the allowed radiation exposure of crewmen performing lunar missions. It is proposed that the radiation dose be divided into three parts as follows:

1) Extra-Vehicular Activity (EVA) Exposure during quiescent solar periods (no solar flare activity) While performing EVA type operations and while in transit to and from the lunar surface, or other unprotected conditions. A period of continuous low level of known radiation exposure will occur. It is proposed that the dose limit for these exposure be set at 5 REM.

2) Emergency exposure While on an extended EVA mission, or during other unprotected conditions, in the event a solar flare occurs and the crewman cannot return to the main solar base where more complete radiation protection is provided, a short period of high level exposure will occur. For this emergency exposure a dose limit of 20 REM is proposed, delivered in a period of 24 hours or less.

3) Exposure within the permanent lunar shelter While within a well shielded habitat, radiation exposure corresponds to the natural radiation background on Earth. It is proposed that this limit level be set at 0 REM.

Under the worst possible conditions the total dose received by any crewman is limited to the sum of the quiescent and emergency doses or 25 REM. To accomplish this level of dose control, quiescent EVA exposure must be limited to 5 REM by measurement and control of individual exposures. Sufficient shielding must be provided for the case where a solar flare is encountered while on an EVA operation to limit the dose in that period to 20 REM, and the main lunar shelter must be shielded to a level that produces an Earth equivalent background radiation level during all periods that a crewman is not performing an EVA operation. Note that the main shelter is not merely a storm shelter, but that it also eliminates the quiescent radiation dose in order to maximize the allowable quiescent dose received during EVA operations.

In this paper no attempt is made to correlate with any specific lunar program or mission. Instead, some of the options that should cover the range of possible missions are considered.

The lunar missions could have durations of a week, a month, or six months and periods of occupancy up to years. Solar flare protection is the primary consideration for the shorter missions up to a month. For the longer missions, the requirement to reduce the constant galactic cosmic ray dose is the primary radiation protection consideration resulting in a heavily shielded habitat. The unshielded galactic cosmic ray dose is on the order of 20 to 50 REM/year. Exploration of the lunar surface, and the establishment of remote scientific stations add additional complications to the radiation problem. Several options to cover the range of missions have evolved as follows:

Buried Lunar Base This base provides a radiation environment equivalent to the background radiation encountered on Earth, and is required for missions of six months or more. A four man base is estimated to require 4,000 cu.ft. interior volume. The resupply time is taken as 180 days. The minimum shielding requirement is 785 grams/cm$^2$, which provides a dose from galactic cosmic rays similar to that on Earth for people living at an altitude of 9000 ft. above sea level. The thickness of the shielding requires that the density of the lunar material as placed upon the shelter be known. Because of tamping problems on the Lunar surface the density might be as low as 1 gm/cm$^3$. This density would require a shield thickness of 7.85 meters. If the upper estimated density of lunar material, 3 gm/cm$^3$ is used, the shield thickness is 2.62 meters. Actual thickness will be determined by on site measurements, while burying is underway. The construction of a buried shelter assumes that construction equipment is on the lunar surface, and should require a number of flights to implement. Thus it is not a candidate for early lunar missions.

Earth Fabricated Solar Flare Storm Shelter This type of shelter is considered applicable for missions of up to about 30 days duration. It is considered capable of supporting four men for a period of up to 10 days, while a solar flare is in progress. Because the total exposure time to Galactic Cosmic Rays is for not more than 30 days the total dose from these rays will be less than 5 REM under the most pessimistic assumptions. The storm cellar needs only to protect against a worst case solar flare by reducing the dose to 20 REM. Such a shelter would require a shield thickness of 59 gm/cm$^2$ of aluminum or a wall of thickness of 8.70" (22 cm). The mass of such a shelter is estimated at 14.7 tons. No provision in this estimate has been made other than interface connections for power, air, communications and control. A small, self-contained waste disposal device is needed. The capability to deliver this shelter to the Moon and to offload, level and connect to the life support, power, and other systems has not been addressed.

An alternate to the thick walled, 4 man storm shelter would be to deliver a thin walled shelter and a small earth moving device. Assuming that the average wall thickness is 3/16", the weight of the storm cellar module delivered from Earth should be ~500-600 lbs (225-275 kg) including only the aluminum shell. For solar flare protection only, covering with lunar soil could be accomplished with a small teleoperated earth mover. Assuming loosely packed lunar soil with a density of 1 $gm/cm^2$, a soil cover of about 2 feet (61 cm) would be required. This would require moving 815 to 850 $ft^3$ of soil depending on burial depth.

Should neither of the above solutions prove feasible, then the mission should be planned for periods of low solar activity. The available solar flare data indicate that no major and very few small flares (which would not impact dose limits) are encountered when the sunspot number is less than about 35. The sunspot activity is below this level for about 4 years as one cycle ends and the next cycle begins.

Lightly Shielded Vehicles on the Lunar Surface These vehicles consist of a pressurized solar flyer or lunar rover, which are operated under shirt sleeve conditions. In the event of a solar flare, the time needed to return to either of the previously discussed shelters may equal the time to deliver in excess of 90% of the total dose from a solar flare (i.e. 6 to 8 hours). These vehicles are assumed to carry a crew of one or two. The mass of shielding to produce a dose of not more than 20 REM for a two man arrangement is ~6 tons of aluminum. The mass is noted as a guide for vehicle design. Since incorporating this amount of mass may not be feasible an inflatable structure which can be buried by a backhoe blade on the surface vehicle should be investigated. The required burial depth is on the order of 2 feet as discussed above.

Partial Protection Garment For operations performed in the spacesuit and also in an unpressurized lunar rover, the return time to a safe shelter is estimated not to exceed 3 hours. Vital repairs may require exposure to high radiation fields. For these conditions a concept for a partial protection garment is described. This garment weighs 375 lbs. (170 kgms). On the lunar surface it is equivalent to carrying 63 lbs (29 kgms) on Earth. It is capable of reducing the radiation level from 5 to 7 times. A trade study is needed between mobility and weight, and detailed work may eliminate unneeded shielding around the back pack area.

## 2.0 INTRODUCTION

Providing radiation protection for extended missions on the lunar surface requires that the following quantities be defined:

- The radiation environment
- The allowed dose of radiation
- The conditions under which radiation exposure will occur
- The attenuation of radiation by shielding materials

With these data defined a range of shielding configurations can be defined and their impact on lunar operations evaluated.

## 3.0 THE RADIATION ENVIRONMENT

There are three natural radiation sources:

- Trapped protons and electrons in the Earth's magnetic field.
- Galactic Cosmic Rays
- Solar Flares (Solar Proton Events)

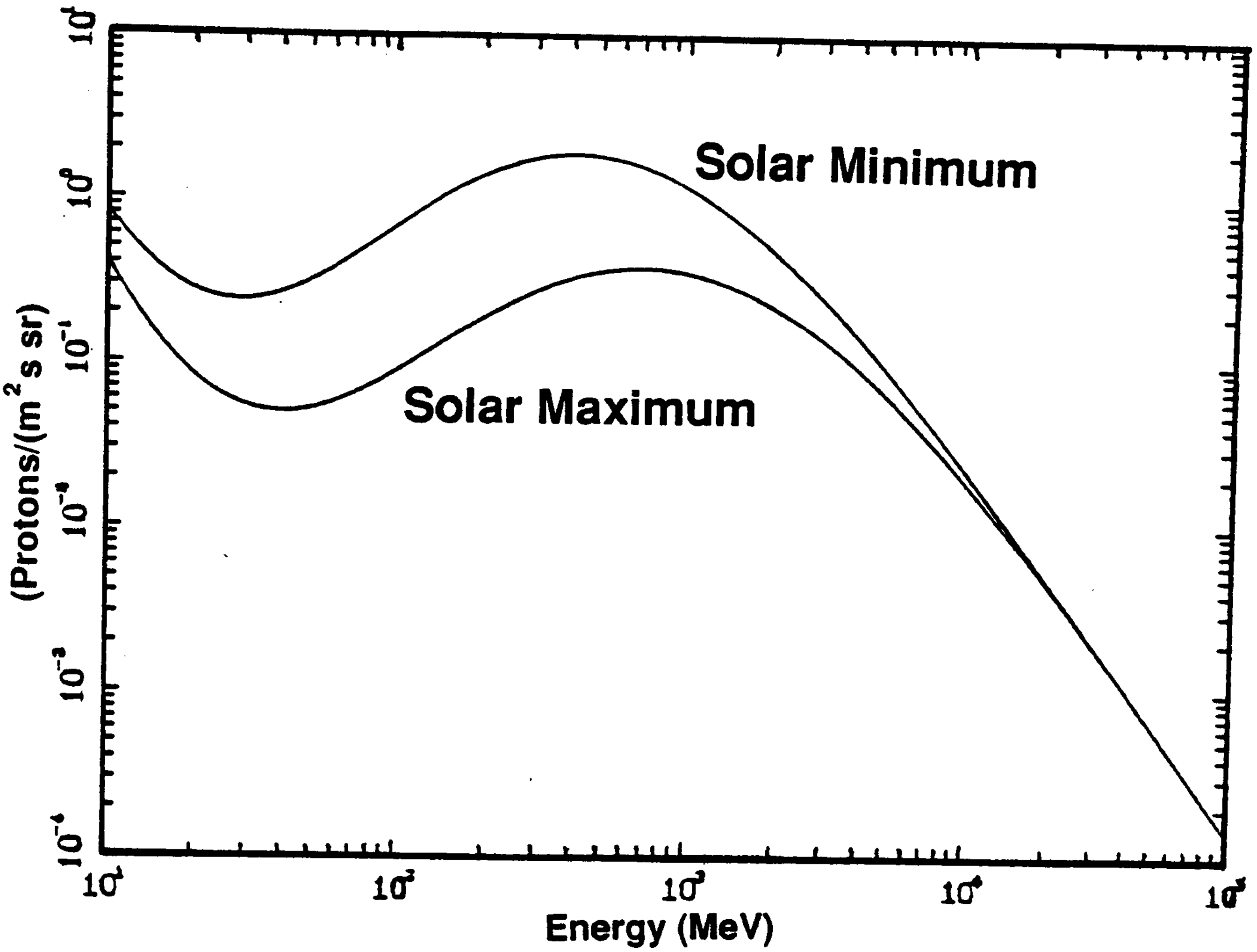
If nuclear power is employed, a fourth source must be taken into account, but it is not considered part of this study. The natural radiation environment provides radiation doses in two different ways. The trapped particles and the galactic cosmic rays cause radiation exposure which is continuous and well documented. Solar flares are random and vary widely in the number of protons they contain and the energy distribution of those protons.

Transit to and from the moon is not part of this study. An allowance for this exposure will be made in the dose portion of this report, but will not be considered in this report.

### 3.1 GALACTIC COSMIC RAYS

The spectra of galactic cosmic rays is shown in Figure 1 from reference 1. These particles are not generated in our solar system.

Figure 1, Galactic Cosmic Radiation Proton Flux (Ref. 1)



Proton spectra in the Naval Research Laboratory (CREME) model of galactic cosmic radiation. Shown are proton fluxes at solar maximum (cosmic ray minimum) and solar minimum (cosmic ray maximum).

They are formed in the galaxy and the mechanism of their formation is not completely understood. The composition of particles in galactic cosmic rays are as follows:

Chemical Composition of Galactic Cosmic Rays

(F. B. McDonald "Review of Galactic and Solar Cosmic Rays, NASA SP-71 SECOND SYMPOSIUM ON PROTECTION AGAINST RADIATIONS IN SPACE pg. 21)

| Group | Atomic Number Z | No./sq m ster sec> > 1.5 GeV/Nuc | Intensity<br>----------<br>Intensity Z>=10 | Average in Universe No./sq. m ster sec > 1.5 Gev/Nuc |
|---|---|---|---|---|
| Hydrogen | 1 | 1300 | 680 | 3360 |
| Helium | 2 | 88 | 46 | 258 |
| Li, Be, B | 3 - 5 | 1.9 | 1.0 | $10^{-5}$ |
| C, N, O, F | 6 - 9 | 5.7 | 3.0 | 2.64 |
| Z >= Neon | >= 10 | 1.9 | 1.0 | 1.0 |
| Z >= Calcium | >= 20 | .53 | .28 | .06 |

Note that in Figure 1 the protons/($m^2$ sec ster) below $10^4$ decrease as the solar activity increases. This is due to the magnetic shielding produced by solar activity.

## 3.2 SOLAR PROTON EVENTS (SOLAR FLARES)

Major solar flares are rare and difficult to predict. In previous flight operations outside the protection of the Earth's magnetic field the durations of the flights were short and only single events needed to be considered. In the case of orbital flights of low inclination, the Earth's magnetic field provided good protection from these events. In the case of a manned lunar base however, the duration of the mission may extend for 180 days thus exposure to several flares may occur. Table 1 is a summary of events in solar cycle 19, which commenced in April 1954 and ended in January 1965, extracted from references 2 and 3. In Table 1 the events have been retabulated to show the total number of days in which solar protons were present

## Table 1, Solar Flare Data For Cycle 19

| EVENT START HOUR | EVENT START DATE | EVENT END HOUR | EVENT END DATE | DURATION DAYS | N(>30MEV) P/SQ.CM. | ENERGY CURVE SLOPE | CHARIS-TIC RIGIDITY | DAYS FROM PREVIOUS EVENT | EVENT + 180 DAYS | TOTAL FLUX NEXT 180 DAYS | TOTAL DAYS WITH FLARES |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0800 | 10/27/51 | 0800 | 10/30/51 | 3.0 | 1e6 | | | 0 | 4/24/52 | 1e6 | 3.0 |
| 1800 | 3/ 2/53 | 1800 | 3/ 5/53 | 3.0 | 1e6 | | | 492 | 8/29/53 | 1.8e6 | 3.5 |
| 1930 | 5/19/53 | 0730 | 5/20/53 | .5 | 8e5 | | | 570 | 11/15/53 | 8e5 | .5 |
| START OF CYCLE 19 APRIL 1954. ASSUMING 11 YEARS PER CYCLE THE CORRESPONDING PERIOD IS 19 APRIL 1998 | | | | | | | | | | | |
| 2200 | 1/17/55 | 2200 | 1/19/55 | 2.0 | 1e6 | | | 608 | 7/16/55 | 1e6 | 2.0 |
| 0430 | 2/23/56 | 1630 | 2/27/56 | 4.5 | 8e9 | -4.0 | 300 | 402 | 8/21/56 | 8e9 | 4.5 |
| 1500 | 8/31/56 | 300 | 9/ 3/56 | 2.5 | 3e7 | | | 190 | 2/27/57 | 3.31e8 | 7.0 |
| 2100 | 11/13/56 | 2100 | 11/17/56 | 2.0 | 1e6 | | | 74 | 5/12/57 | 3.02e8 | 7.0 |
| 1500 | 1/20/57 | 300 | 1/23/57 | 2.5 | 3e8 | -2.8 | | 68 | 7/19/57 | 3.12e8 | 12.0 |
| 1500 | 4/ 3/57 | 300 | 4/ 6/57 | 2.5 | 1e6 | | | 73 | 9/30/57 | 7.42e7 | 22.5 |
| 1300• | 6/21/57 | 1300 | 6/23/57 | 2.0 | 1e6 | | | 79 | 12/18/57 | 8.32e7 | 21.0 |
| 0530• | 6/22/57 | 530 | 6/25/57 | 3.0 | | | | 1 | 12/19/57 | | |
| 0845 | 7/ 3/57 | 845 | 7/ 5/57 | 2.0 | 1e7 | -3.5 | | 11 | 12/30/57 | 8.22e7 | 16.0 |
| 2030 | 7/24/57 | 830 | 7/25/57 | .5 | VS | | | 21 | 1/20/58 | 7.22e7 | 14.0 |
| 0030• | 8/29/57 | 1230 | 8/29/57 | .5 | 5e7 | -3.5 | | 36 | 2/25/58 | 7.72e7 | .0 |
| 1300• | 8/29/57 | 1300 | 8/31/57 | 2.0 | | -3.5 | | 0 | 2/25/58 | | |
| 1530• | 8/31/57 | 1530 | 9/ 2/57 | 2.0 | | -3.5 | | 2 | 2/27/58 | | |
| 1730• | 9/ 2/57 | 1730 | 9/ 4/57 | 1.5 | | -3.5 | | 2 | 3/ 1/58 | | |
| 0900 | 9/12/57 | 2100 | 9/15/57 | 3.5 | 9e6 | -3.5 | | 10 | 3/11/58 | 2.72e7 | 8.5 |
| 1630• | 9/21/57 | 1630 | 9/23/57 | 2.0 | 3.2e6 | -3.5 | | 9 | 3/20/58 | 1.82e7 | 5.0 |
| 2315• | 9/26/57 | 2315 | 9/27/57 | 1.0 | | -3.5 | | 5 | 3/25/58 | | |
| 0630 | 10/21/57 | 630 | 10/22/57 | 1.0 | 1e7 | -3.5 | | 25 | 4/19/58 | 4.15e8 | 10.5 |
| 0700 | 2/10/58 | 700 | 2/11/58 | 1.0 | 5e6 | -3.5 | | 112 | 8/ 9/58 | 9.08e8 | 15.5 |
| 1830• | 3/23/58 | 600 | 3/25/58 | 1.5 | 4e8 | -3.6 | 80 | 41 | 9/19/58 | 9.73e8 | 23.5 |
| 1300• | 3/25/58 | 100 | 3/30/58 | 4.5 | | -3.6 | | 2 | | | |
| 1000 | 4/10/58 | 2200 | 4/12/58 | 2.5 | 1e6 | | | 16 | 10/ 7/58 | 5.758e8 | 21.0 |
| 1345 | 6/ 6/58 | 1345 | 6/ 7/58 | 1.0 | 1e6 | | | 57 | 12/ 3/58 | 5.748e8 | 18.5 |
| 0130 | 7/ 7/58 | 130 | 7/11/58 | 4.0 | 5e8 | -3.4 | | 31 | 1/ 3/59 | 5.738e8 | 17.5 |
| 0405 | 7/29/58 | 405 | 7/30/58 | 1.0 | 1e6 | -3.5 | | 22 | 1/25/59 | 7.38e7 | 13.5 |
| 0600 | 8/16/58 | 1800 | 8/18/58 | 2.5 | 2e7 | -3.5 | | 18 | 2/12/59 | 7.28e7 | 12.5 |
| 1500• | 8/21/58 | 300 | 8/23/58 | .5 | 5e7 | -3.2 | | 5 | 2/17/59 | 7.28e7 | 10.0 |
| 1530• | 8/22/58 | 330 | 8/27/58 | 3.5 | | -3.2 | | 1 | 2/18/59 | | |
| 0400• | 8/26/58 | 1600 | 8/28/58 | 2.5 | | | | 4 | 2/22/59 | | |
| 1530 | 9/22/58 | 330 | 9/26/58 | 3.5 | 2.8e6 | -3.5 | | 27 | 3/21/59 | 2.8e6 | 3.5 |
| 2300 | 5/10/59 | 1100 | 5/16/59 | 5.5 | 1.2e9 | -3.1 | 65-70 | 230 | 11/ 6/59 | 7.001e9 | 21.5 |
| 0400• | 7/10/59 | 400 | 7/14/59 | 4.0 | 5.8e9 | -1.6 | 90 | 61 | 1/ 6/60 | 5.801e9 | 16.0 |
| 0700• | 7/14/59 | 700 | 7/17/59 | 3.0 | | -2.3 | 68 | 4 | 1/10/60 | | |
| 0200• | 7/17/59 | 200 | 7/24/59 | 7.0 | | -2.2 | 66-125 | 3 | 1/13/60 | | |
| 0400 | 9/ 2/59 | 400 | 9/ 4/59 | 2.0 | 1e6 | | | 47 | 2/29/60 | 7e6 | 3.5 |
| 0700 | 1/12/60 | 1900 | 1/13/60 | 1.5 | 6e6 | | | 132 | 7/10/60 | 8.77e7 | 13.9 |
| 0800• | 3/29/60 | 2000 | 3/30/60 | 1.5 | 4.7e6 | -3.5 | | 77 | 9/25/60 | 8.17e7 | 14.9 |
| 2000• | 3/30/60 | 400 | 4/ 1/60 | 1.3 | | -4.0 | | 1 | 9/26/60 | | |
| 0930• | 4/ 1/60 | 930 | 4/ 3/60 | 2.0 | | -3.5 | 155 | 2 | 9/28/60 | | |
| 0800• | 4/ 5/60 | 2000 | 4/ 6/60 | 1.5 | | -4.0 | | 4 | 10/ 2/60 | | |
| 0200^ | 4/28/60 | 200 | 4/29/60 | 1.0 | 2.5e7 | -4.9 | 150-240 | 23 | 10/25/60 | 7.7e7 | 8.6 |
| 0600^ | 4/29/60 | 1800 | 4/30/60 | 1.5 | | -4.9 | 105 | 1 | 10/26/60 | | |

Table 1, Solar Flare Data For Cycle 19 (Continued)

| EVENT START HOUR | EVENT START DATE | EVENT END HOUR | EVENT END DATE | DURATION DAYS | N(>30MEV) P/SQ.CM. | ENERGY CURVE SLOPE | CHARIS-TIC RIGIDITY | DAYS FROM PREVIOUS EVENT | EVENT + 180 DAYS | TOTAL FLUX NEXT 180 DAYS | TOTAL DAYS WITH FLARES |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1030• | 5/ 4/60 | 1030 | 5/ 9/60 | .1 | 1.2e7 | -1.9 | 280 | 5 | 10/31/60 | 5.2e7 | 6.1 |
| 1800• | 5/ 6/60 | 1800 | 5/ 8/60 | 2.5 |  |  | 235 | 2 | 11/ 2/60 | 4e7 | 6.0 |
| 0800 | 5/13/60 | 1135 | 5/14/60 | 1.0 | 1e5 |  |  | 7 | 11/ 9/60 | 4e7 | 3.5 |
| 0500 | 9/ 3/60 | 1700 | 9/ 5/60 | 2.5 | 4e7 | -1.9 | 150-225 | 113 | 3/ 2/61 | 4.8e9 | 8.0 |
| 1400• | 11/12/60 | 200 | 11/15/60 | 2.5 | 4.7e9 | -2.2 | 95-185 | 70 | 5/11/61 | 4.76e9 | 5.5 |
| 0900• | 11/15/60 | 1800 | 11/16/60 | 1.5 |  | -2.2 |  | 3 | 5/14/61 | 6e7 | 3.0 |
| 0200 | 11/21/60 | 1400 | 11/23/60 | 1.5 | 6e7 | -1.9 | 100-375 | 6 | 5/20/61 | 6e7 | 1.5 |
| 1300• | 7/12/61 | 100 | 7/15/61 | 2.5 | 1.2e7 | -1.2 | 45-60 | 239 | 1/ 8/62 | 4.4e8 | 8.0 |
| 1700• | 7/15/61 | 300 | 7/16/61 | .4 |  |  |  | 3 | 1/11/62 |  | 5.5 |
| 1200 | 7/18/61 | 1200 | 7/20/61 | 2.0 | 2.6e8 | -1.8 | 100-160 | 3 | 1/14/62 | 4.28e8 | 5.1 |
| 2355 | 9/28/61 | 2355 | 9/30/61 | 2.0 | 1.6e8 |  | 210 | 72 | 3/27/62 | 1.68e8 | 3.1 |
| 1800 | 11/10/61 | 1800 | 11/12/61 | 1.1 | 8e6 |  |  | 43 | 5/ 9/62 | 8e6 | 1.1 |

NO FLARES FROM 11/12/61 TILL 4/1/54< APPROXIMATE END OF CYCLE 6-64

• RELATIVISTIC PARTICLES DETECTED

^ OVER LAPPING

in each 180 days from the start of each event. The total flux of protons in that 180 days is also given.

The number of solar proton events are roughly correlated with the sunspot number as can be seen in Figure 2 from reference 4. Solar activity was higher during Cycle 19 than any of the other cycles from cycle 18 thru 21 as can be seen by noting the monthly sunspot number in Figure 3, also supplied by reference 4. Cycle 19 is assumed to be a conservative representation of total number of solar events that will occur in cycle 22, which is estimated to commence about April 1998, and which is around the period when lunar exploration is planned.

It is interesting to note that the larger events appear to occur when the sun spot number is either increasing or decreasing, but not at the maximum. The largest events on record, $\sim 10^{10}$ total protons per $cm^2$ with energies above 30 Mev occurred between two and three years either before or after peak sun spot activity in cycles 19 and 20.

A crude estimate of the dose rate during each event under EVA operations on a lunar plane (2pi steradians provide the flux) is given in Table 2. A description of the method used to estimate dose is given in the section on shielding.

The data indicates that early in the solar cycle, year 1 and 2, one to three 180 day missions might be performed in which no solar flare is encountered. There are also periods at higher solar activity when the time between flares is from 112 to 230 days, but the time between flares tends to decrease with increase in the sun spot number or toward the middle of the sun spot cycle. Typical flares last from 1.5 to 4.5 days, but the flares from multiple events beginning July 10, 1959 lasted until July 20, 1959, a total of 10 days of continuous flare activity. Many of the flares do not cause a large dose of radiation, but in the case of multiple overlapping flares the later flare may be the large dose contributor.

Two methods are used to describe the spectral variation of a solar proton event. These methods are curve fitting techniques that establish a mathematical description of the solar proton event. For simplicity a linear relationship is sought.

Figure 2, Event integrated proton fluxes above 30 Me V for the major solar events of the 19th and 20th solar cycles (King, 1974 Ref. 4)

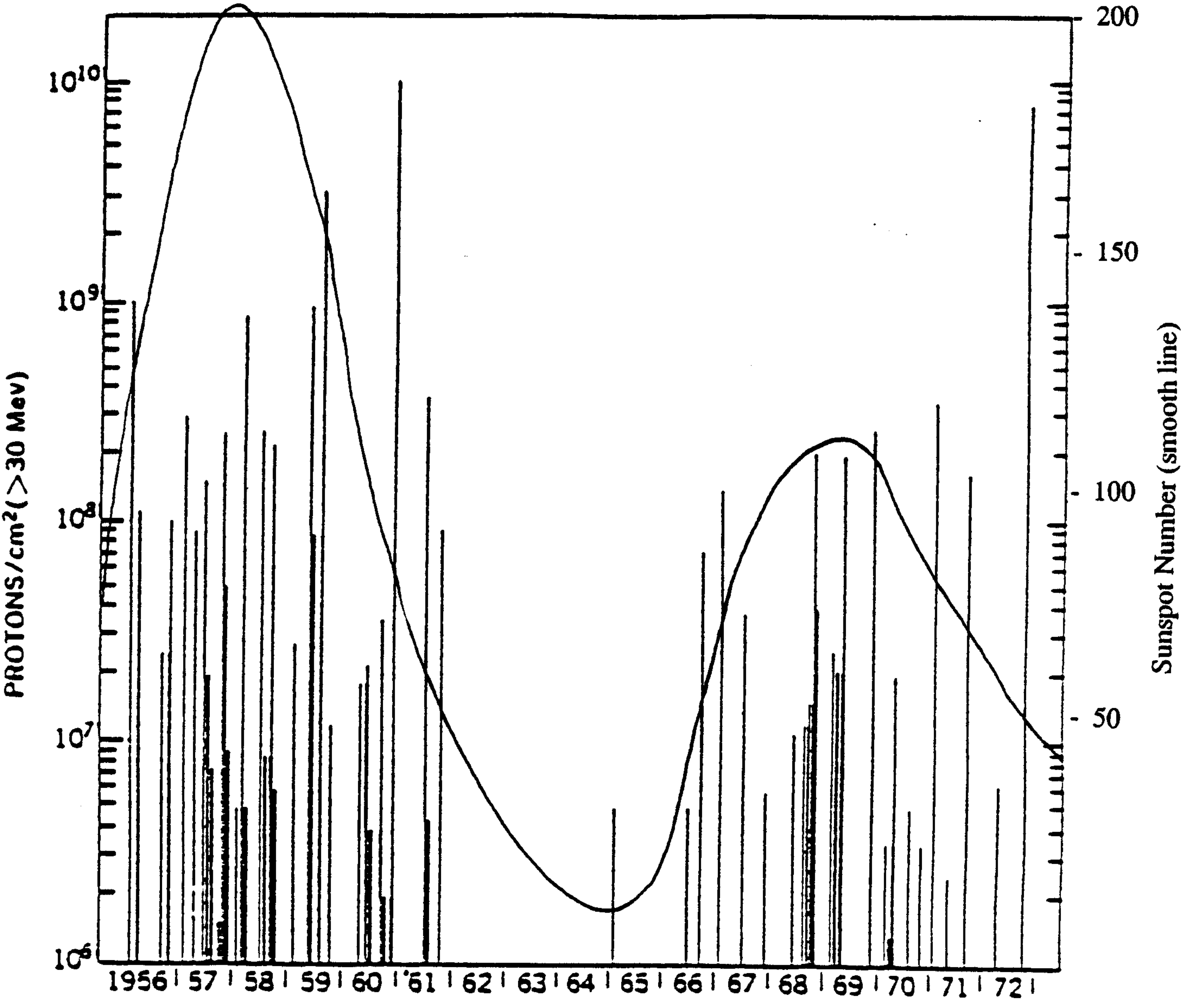


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Figure 3, Sunspot Quantity For Four Cycles (Ref. 4)

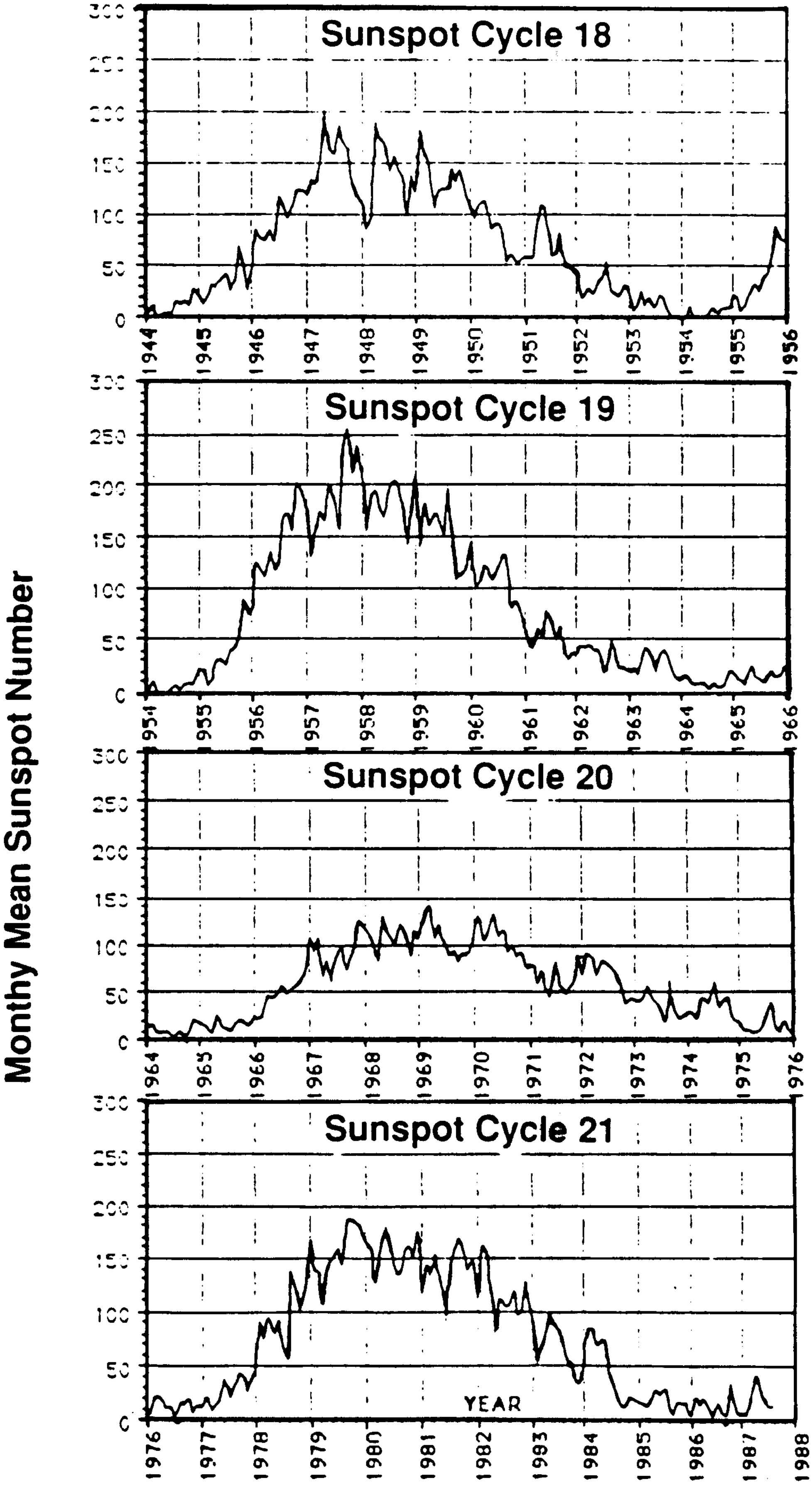


Table 2, Time Variation of Flare Parameters During Cycle 19

| DAY-HOUR | EVENT DATE | J' (P/CM^2 SEC STER) | P' RIGIDITY MV | N(>30MEV) | DOSE/HR RADS/HR |
|---|---|---|---|---|---|
| 23-0400 ONSET | 2/23/56 | | | | |
| 23-1930 | | 2479 | 300 | 257.6 | .758 |
| 23-2200 PEAK | | 2478 | 300 | 258.0 | .759 |
| 28-0700 END | | | | | |
| 23-1500 ONSET | 3/23/58 | | | | |
| 25-0100 PEAK | | 443 | 80 | 4.0 | .005 |
| 26-1400/1815 | | 640 | 80 | 32.3 | .038 |
| 25-2000 END | | | | | |
| 11-0030 ONSET | 5/10/59 | | | | |
| 12-0230 PEAK | | 45261 | 65 | 1,145.1 | .984 |
| 12-0500 | | 30000 | 65 | 759.0 | .652 |
| 12-0520/0915 | | 18000 | 70 | 592.2 | .562 |
| 12-0915/1335 | | 4100 | 70 | 134.9 | .128 |
| 12-1335/1750 | | 2800 | 66 | 74.9 | .064 |
| 18-0230 END | | | | | |
| 7-0700 ONSET | 7/10/59 | | | | |
| 11-0755/1625 | | 7800 | 90 | 548.0 | .756 |
| 11-1200 PEAK | | 19704 | 90 | 1,384.4 | 1.910 |
| 12-1225/2345 | | 2100 | 90 | 147.5 | .204 |
| 25-0700 END | | | | | |
| 14-0730 ONSET | 7/14/59 | | | | |
| 15-0330 PEAK | | 50240 | 68 | 1,495.0 | 1.353 |
| 15-13301555 | | 35000 | 68 | 1,041.5 | .942 |
| 17-0730 END | | | | | |
| 17-0000 ONSET | 7/16/59 | | | | |
| 17-1000 PEAK | | 14960 | 125 | 2,210.9 | 4.001 |
| 17-1200 | | 3200 | 125 | 472.9 | .856 |
| 17-1555/1935 | | 1100 | 113 | 132.7 | .240 |
| 18-1400 | | 800 | 90 | 56.2 | .077 |
| 18-1350/1640 | | 2800 | 70 | 92.1 | .088 |
| 20-1445 | | 300 | 66 | 8.0 | .007 |
| 19-1900 END | | | | | |
| 1-1000 ONSET | 4/ 1/60 | | | | |
| 1-1020 | | 10 | 155 | 2.1 | .004 |
| 1-1600 PEAK | | 252 | 155 | 53.9 | .112 |
| 4-1100 END | | | | | |
| 28-0230 ONSET | 4/28/60 | | | | |
| 28-1250 | | 2.4 | 240 | .9 | .002 |
| 28-1430 PEAK | | 83 | 240 | 30.7 | .075 |
| 29-0300 | | 1.9 | 150 | .4 | .001 |
| 29-0830 END | | | | | |

Table 2, Time Variation of Flare Parameters During Cycle 19 (continued)

| DAY-HOUR | EVENT DATE | J' (P/CM^2 SEC STER) | P' RIGIDITY MV | N(>30MEV) | DOSE/HR RADS/HR |
|---|---|---|---|---|---|
| 29-0500 ONSET | 4/29/60 | | | | |
| 29-0500 | | 440 | 105 | 45.2 | .072 |
| 1-0800 PEAK | | 1130 | 105 | 116.0 | .184 |
| 1-1700 END | | | | | |
| 4-1030 ONSET | 5/ 4/60 | | | | |
| 4-1230 PEAK | | 144 | 280 | 61.3 | .140 |
| 4-1630 | | 6.7 | 280 | 2.9 | .007 |
| 4-1830 END | | | | | |
| 6-1800 ONSET | 5/ 5/60 | POSSIBLE ERROR IN DATES | | | |
| 5-1700/0200 | | 5.8 | 235 | 2.1 | .005 |
| 8-0400 PEAK | | 660 | 235 | 238.7 | .580 |
| 8-1800 END | | | | | |
| 3-0500 ONSET | 9/ 3/60 | | | | |
| 3-0900 | | 42 | 225 | 14.5 | .035 |
| 3-0930/1730 | | 60 | 180 | 15.9 | .036 |
| 4-1650/2320 | | 26 | 150 | 5.3 | .011 |
| 4-2300 | | 12 | 155 | 2.6 | .005 |
| 5-1200 PEAK | | 106 | 225 | 36.6 | .089 |
| 6-0400 | | 7.2 | 120 | 1.0 | .002 |
| 7-0530 | | 4 | 120 | .5 | .001 |
| 6-2200 END | | POSSIBLE ERROR | | | |
| 12-1400 ONSET | 11/12/60 | | | | |
| 12-1930 | | 1100 | 280 | 468.5 | 1.070 |
| 12-2000 | | 1250 | 240 | 461.8 | 1.123 |
| 13-0200 | | 3400 | 185 | 934.2 | 2.113 |
| 13-0600 PEAK | | 8156 | 280 | 3,473.6 | 7.936 |
| 13-0800 | | 3400 | 155 | 727.5 | 1.514 |
| 13-1305 | | 3000 | 120 | 409.4 | .741 |
| 13-1830/2000 | | 2800 | 95 | 226.2 | .328 |
| 13-2230 | | 1000 | 105 | 102.7 | .163 |
| 14-0500 | | 1000 | 95 | 80.8 | .117 |
| 15-1700 END | | | | | |
| 15-0430 ONSET | 11/15/60 | | | | |
| 15-0500 | | 250 | 375 | 132.2 | .353 |
| 15-1130 | | 320 | 240 | 118.2 | 1.123 |
| 15-1030-1230 | | 285 | 175 | 72.7 | .161 |
| 15-1930 PEAK | | 6196 | 375 | 3,275.8 | 8.744 |
| 15-2130 | | 3300 | 120 | 450.3 | .741 |
| 16-0930 | | 1000 | 100 | 91.6 | .149 |
| 16-1430/1730 | | 300 | 100 | 27.5 | .045 |
| 18-1130 END | | | | | |

Table 2, Time Variation of Flare Parameters During Cycle 19 (continued)

| DAY-HOUR | EVENT DATE | J' (P/CM^2 SEC STER) | P' RIGIDITY MV | N(>30MEV) | DOSE/HR RADS/HR |
|---|---|---|---|---|---|
| 12-1300 ONSET | 7/21/61 | | | | |
| 13-0010 | | 850 | 60 | 15.8 | .011 |
| 13-1200 PEAK | | 28447 | 60 | 529.8 | .371 |
| 13-0900/1820 | | 5450 | 46 | 30.2 | .010 |
| 14-1745 | | 1200 | 45 | 5.9 | .002 |
| 15-1300 END | | | | | |
| 18-1130 ONSET | 7/18/60 | | | | |
| 18-1535/1750 | | 500 | 160 | 112.3 | .240 |
| 18-1720 | | 1000 | 150 | 203.2 | .421 |
| 18-1930 PEAK | | 1554 | 160 | 348.9 | .746 |
| 18-2100/2330 | | 1100 | 135 | 187.3 | .364 |
| 18-2335 | | 700 | 130 | 111.3 | .212 |
| 19-0300 | | 430 | 125 | 63.5 | .119 |
| 19-0650 | | 260 | 120 | 35.5 | .064 |
| 19-2000 | | 210 | 100 | 19.2 | .029 |
| 20-1310 | | 120 | 90 | 8.4 | .011 |
| 21-0200 | | 100 | 90 | 7.0 | .010 |
| 22-0100 | | 60 | 80 | 3.0 | .004 |
| 20-1830 END | | | | | |

The first method is a power law description. For the integral flux over time (N) to the end of the event:

$$N(>E) = AE^{-m} \qquad p(>E)/cm^2 \qquad (1)$$

or for the intensity (n) case

$$1/4\, pi\, (dN(>E))/dt = n(t) = A'(t)E^{-m'(t)} \qquad p\,(>E)/cm^2 \text{ sec ster} \qquad (1a)$$

In these equations A, A', m and m' are arbitrary constants determined by the curve fit. E is an energy level, t is time at which n was measured. Writing equation (1) in logarithmic form in order to establish a linear relationship

$$\log(N(>E) = \log A - m\log E \qquad (2)$$

Defining a change in variables let:

Let $\log (N>E) = y$, $\log A = b$ and $\log E = x$

Then:

$$y = -mx + b \qquad (2a)$$

Equation 2a is a straight line, the desired linear relationship. This type of curve is typically plotted on log-log paper. Log A is the y intercept, and -m is the slope.

The second method is a description is in terms of rigidity:

Rigidity, P, is a measure of momentum and is a measure of the latitude at which particles of this momentum cannot penetrate the Earth's magnetic field. Rigidity is measured in volts. Many Solar proton flux measurements have been made either at the Earth's surface or at relatively low altitudes and latitudes where low energy particles cannot be detected. Many different measurements are combined to achieve a complete flare description, but for dose and shielding purposes only the summation of these results are required. Rigidity and energy are related by the expression:

$$(Pze)^2 = E^2+2Em_o \qquad (3)$$

substituting for $m_o$ and ze

$$P =(E^2+1{,}876E)^{1/2} \qquad (3a)$$

Where z is the number of charges, e is the charge of an electron and $m_o$ is the rest mass of the proton, 938.23 Mev. For protons, ze = 1. Note that equation 3 has units of energy squared. In electrostatics qV (charge times voltage) has the units of energy, and P in equation 3 has the units of volts.

In this case, the curve fit results in a description that is in exponential form for the total event:

$$N(>P) = B\exp(-P/P') \qquad p(>P)/cm^2 \qquad (4)$$

or for intensity at some time in the event

$$(1/4pi)\,(dN(>P)/dt) = n = B'\exp(-P/P') \qquad p(>P)/cm^2\ sec\ ster \qquad (4a)$$

Taking the natural logs of both sides of equation 4 gives

$$\ln N(>P)= \ln B - P/P' \qquad (5)$$

In equations 4, 4a, and 5, P' is a characteristic rigidity. Then let $\ln\{N(>P)\} = y$, $\ln B = b$ (a constant, the intercept at P = 0) and $P = x$, $-1/P' = m$.

$$y = -mx + b$$

This form yields a straight line, the desired linear relationship of a semilog graph.

The slopes of the intensity or flux curves are measures of the penetrating power through a shield. The larger the value of m in Equations 1 and 1a, the fewer high energy particles that the flare contains. In Equations 4 and 4a the characteristic rigidity, P', is inversely proportional to the slope hence the smaller the value of P', the fewer high energy particles in a solar event. In the energy form the slope of equation 1a has been shown to vary from about 2 to 5. This power varies from event to event and varies during an event. In any single event after peak intensity is reached the magnitude of the slope (-m) tends to increase with time--that is, the more energetic particles tend to arrive more quickly than those of lower energy. Values for m in equation 1 for the total flux in some events are tabulated in Table 1. Reference 6 tabulates N(>30 Mev) and P' in the rigidity equation for a series of time periods in a large number of events, which are also shown in Table 1. Some idea of the variation between the spectra of various events can be seen in Figure 4 from reference 6.

Thus far the exposure to radiation has been based upon the total flux encountered, and the intensity or rate of delivery of protons has not been considered. As stated in the Executive Summary, it is proposed that the main lunar shelter provide an environment in which the radiation levels correspond to the natural background levels on Earth. For extended exploration missions shielding is required to limit the dose received by a crewman in 24 hours or less to 20 REM. As will be seen in later sections of this report, this requires that either massive shielding be incorporated into lunar exploration vehicles or that retreat to the permanent shelter be accomplished in a short period of time.

This shielded volume away from the base is small and stay times in this volume under worst case conditions, such as the event starting on 10 July 1959 or the event starting on 2 August 1972, can exceed 10 days. The time variation in solar proton intensity for the August 1972 event is shown in Figure 5 from reference 4 to illustrate this event's duration. It may be possible to reduce the requirement to provide emergency shielding if retreat to the main lunar shelter can be carried out in a short period of time. The total emergency dose may be lower for the retreat case than the use of an emergency shielded space for the entire period of the flare. The time variation of intensity of a solar flare is typically a steep exponential rise to some maximum value of intensity followed by an exponential decay back to background levels.

Figure 4, Proton Flux for Six Solar Flares (Ref. 6)

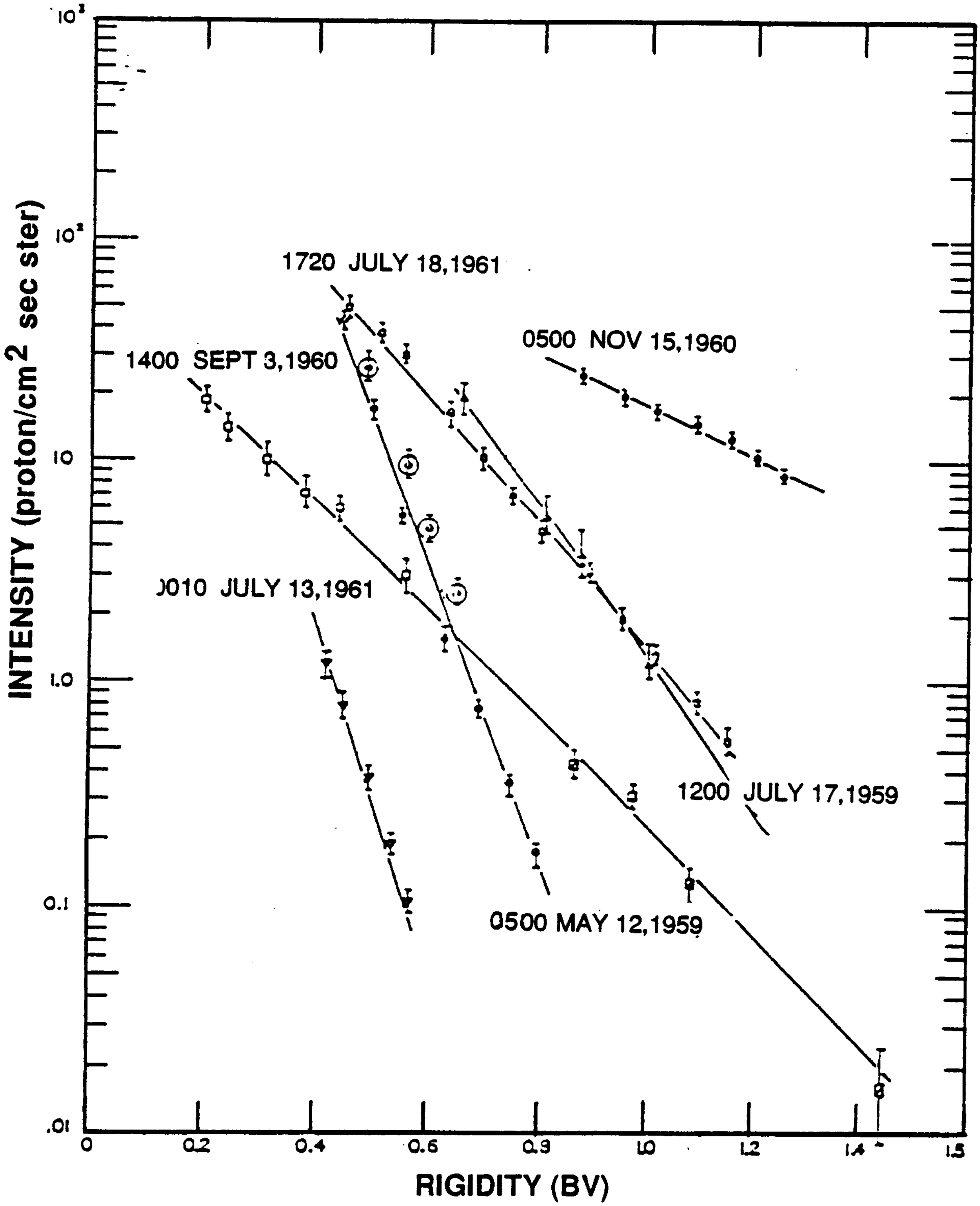
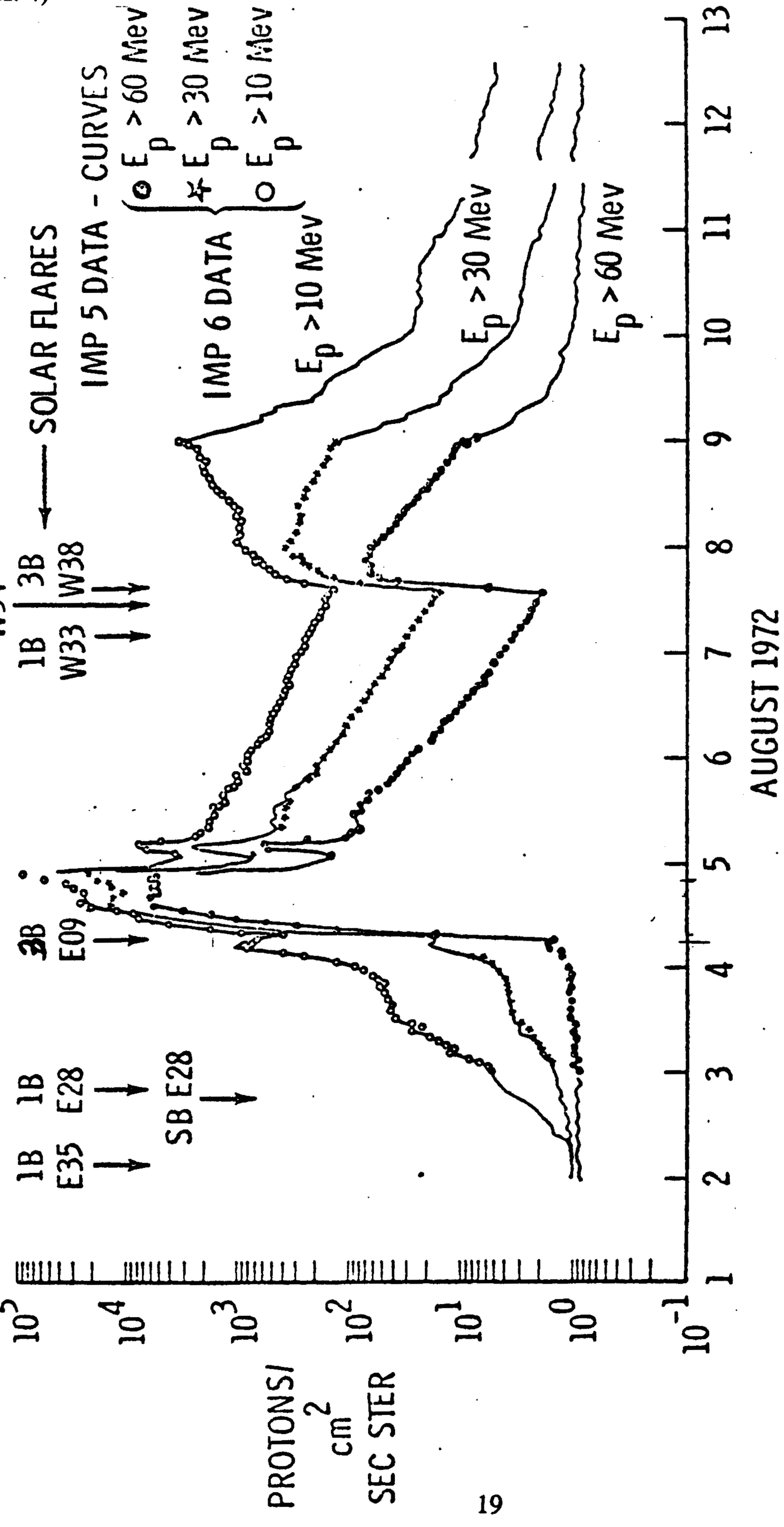


Figure 5, Solar Proton Flux - August 2-12, 1972, Solar Proton Monitoring Experiment (IMP 5 and 6) (Ref. 4)



The following equations describe the rise and decay phases.

For the rise phase:

$$I_r(t_1) = I_{max}\exp(t_{max} - t_1)/t_r$$
$$t_o > t_1 < t_{max} \qquad (6)$$

Where:

$I_r(t_1)$ is the intensity at time $t_1$.

$I(t_{max})$ is the peak intensity.

$t_1$ is the elapsed time since first protons were detected, $t_o$.

$t_r$ is a characteristic rise time constant.

$t_{max}$ is the time of maximum intensity

For the decay phase:

$$I_d(t_2) = I_{max}\exp(-t_2/t_d) \qquad \text{p/cm}^2 \text{ sec ster} \qquad (7)$$
$$t_{max} < t_2 < t_{end}$$

Where:

$I_d(t_2)$ is the intensity at time $t_2$.

$t_2$ is the elapsed time since peak intensity, $t_{max}$.

$t_d$ is a characteristic decay constant.

Typical characteristic rise times are from 6 to 16 hours for the high energy protons but, as can be seen in Figure 5, there was a period of about 30 hours when the intensity above 30 Mev was rising slowly. Typical characteristic decay constants are from 15 to 30 hours. In some cases a second or third flare may occur during the decay period of the initial flare.

Table 2, which is based upon the data in references 2 and 3, shows the start time, peak time, and end time for various events. The parameters J' (B' in equation 4a) and P' are tabulated at various times during the flare. Using this data an estimate of intensity, protons (30Mev)/cm$^2$ per second, at various times can be made. This intensity data provides some guidance in determining dose rates (see Table 2) while a flare is occurring in the event that a decision is made to return from an extended EVA mission or emergency operations outside a shielded area must be performed during a flare. In Figure 5 it can be seen that the peak intensity of protons greater than 30 Mev on August 4, 1972 was about a factor of ten greater than any of the peak intensities in cycle 19.

The maximum credible exposure to solar protons over a 180 day period is required to do shielding calculations. In Table 1 the maximum total number of protons is 8 x $10^9$ protons (>30Mev)/$cm^2$, which occurred in the flare of February 23, 1956. The August 1972 event is estimated at $9x10^9$ protons (>30 Mev)/$cm^2$. This latter event had a steeper slope than the February 1956 event, hence this flare had fewer high energy protons, and, as can be seen in Figure 6 from reference 4, this results in a lower dose behind shielding of thickness greater than 20 gm/cm2.

For purposes of shielding thickness estimation a model event is postulated in which the integral flux above 30 Mev. and a slope in either energy exponent or a characteristic rigidity must be postulated. Figure 7 shows the probability distribution of integral flux size for solar cycle 19 from references 2 and 3. From this plot it is estimated that the maximum size event that should be encountered is $1x10^{10}$ protons(>30Mev)/cm2. The selection of a slope in either equation 1 or 4 is over the duration of the flare. The energy exponent is not as straightforward. A typical value of a moderate slope ($m = -3.12$) has been assumed. These parameters have been applied to achieve a total dose of 20 REM for the duration of the model flare event.

For emergency dose calculations where retreat to the permanent lunar base is required in a period less than the total flare duration, a model intensity (protons/$cm^2$ steradian second) is required for dose rate estimation. From Figure 5 it is estimated that the period where the intensity was within 10 percent of the peak intensity was 14 hours. Estimating that 90 percent of the flare dose was delivered in that period, using the total flux of the proposed model event, N(>30 Mev) = $1x10^{10}$ protons, and for simplification, assuming that the intensity was constant over a 14 hour period for the model event, yields an intensity of $1.4x10^4$ protons/$cm^2$ second steradian.

This intensity is about the peak value observed in the August 1972 event and is postulated for evaluating dose while returning to the lunar base.

Figure 6, Free Space Dose vs. Thickness For February 56 & August 72 Events (Ref. 4)

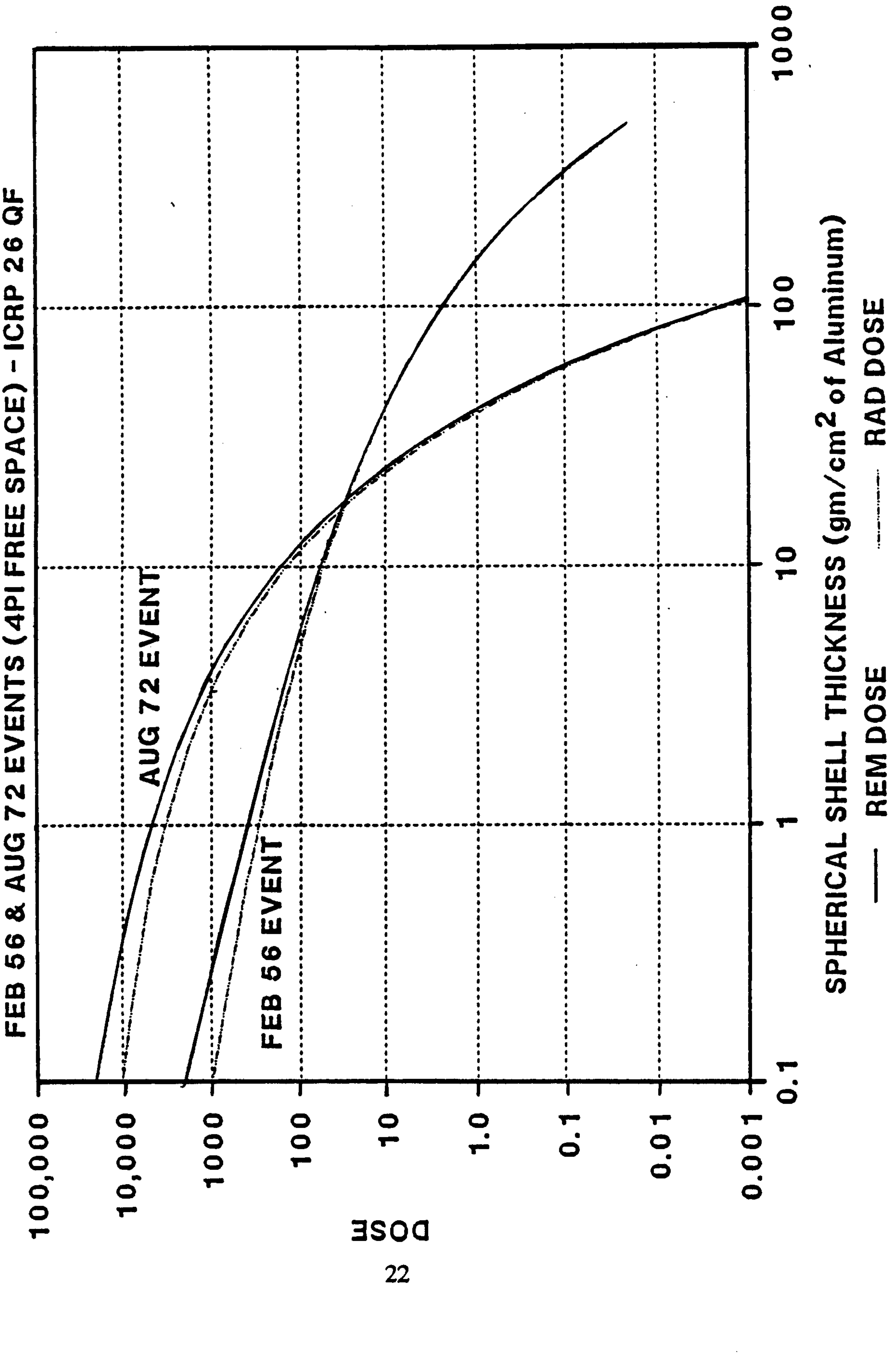
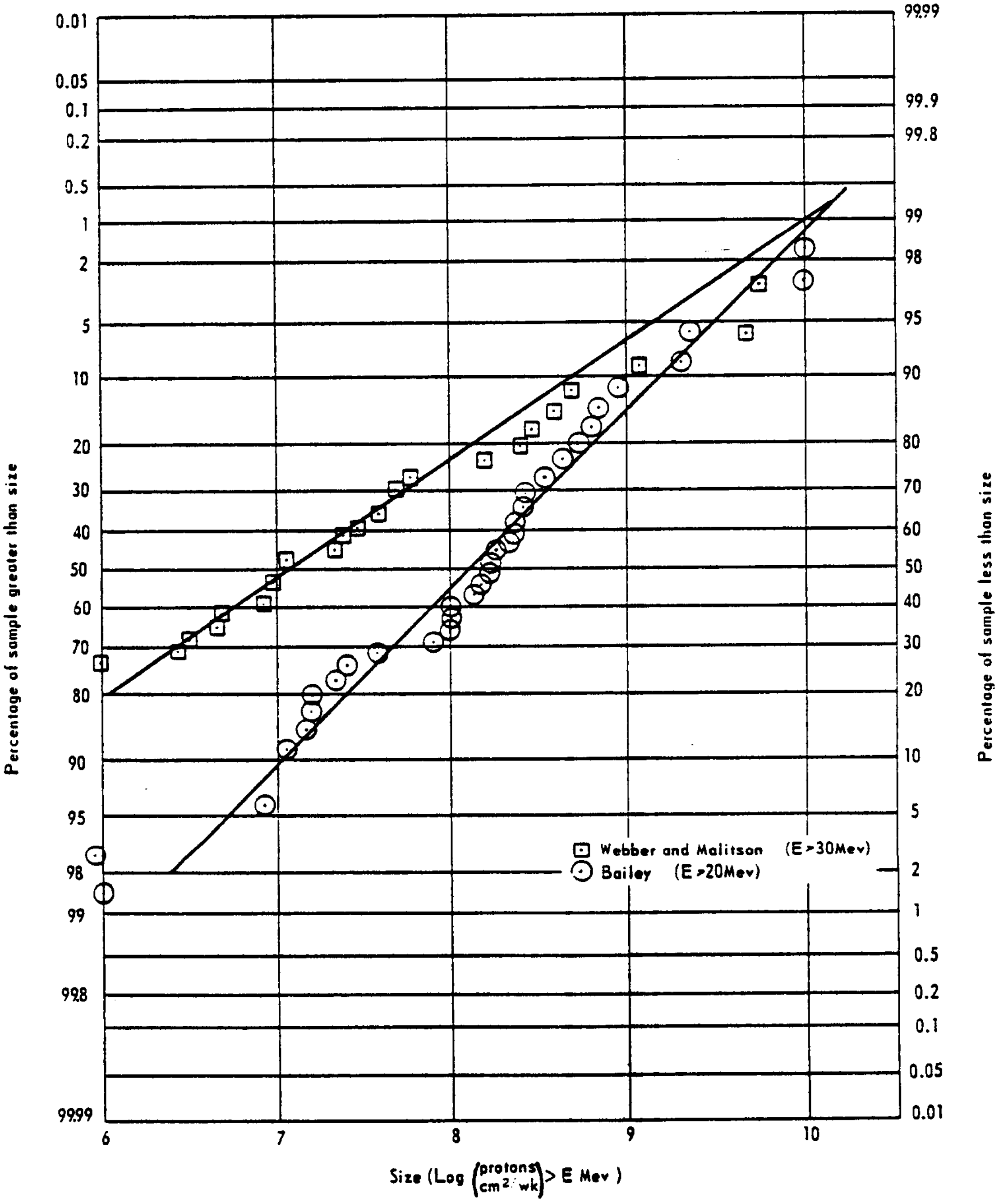


Figure 7, Probability plot of size log (protons/$cm_2$/week) (P > E Mev) for Webber and Malitson, and Bailey data (Reference 2 and 3).



## 4.0 DOSE CONSIDERATIONS

The definitions of the units of radiation dose are as follows:

> ROENTGEN: An exposure to X or gamma radiation such as to produce 1 electrostatic unit (esu) of charge per cc of dry air at standard conditions, which is the equivalent of the deposition of 83 ergs/gram of dry air. This was the earliest unit of radiation exposure. It measures the intensity of radiation incident on the body. The whole body was assumed to be exposed uniformly, and no variation in the energy deposition at different sites in the body was considered.
>
> RAD (Radiation Absorbed Dose): 100 ergs/gram deposited in any medium. The advent of more sophisticated measuring devices made the use of this unit possible.
>
> RBE (Relative Biological Effectiveness): The RBE is a factor which is used to compare the biological effectiveness of absorbed radiation doses (i.e. RADS) due to different types of ionizing radiation. More specifically, it is the ratio of an absorbed dose of X or gamma rays to the absorbed dose of a certain particulate radiation required to produce an identical effect in a particular experimental organism or tissue.
>
> REM (Roentgen Equivalent Man): The REM is the unit used to express human biological dose or damage done as a result of exposure to one of many types of ionizing radiation. The dose in REMs is equal to the absorbed dose in RADs times the RBE factor of the type of radiation being absorbed. Thus REM is a unit of RBE dose.

The present allowed doses in REM units under current flight rules are shown in Table 3 from reference 4. Since all of the dose received by a crewman may be in one flare in one or two days, the 30 day limit of 25 REM at a depth of 5 cm is taken as the limit for all missions of up to 180 days duration. It is proposed to separate this dose into three components as follows:

> EVA AND TRANSIT DOSE: The dose received under unshielded conditions such as EVA operations and lightly shielded conditions such as transit to and from the Earth to the Moon.
>
> Allowed dose = 5 REM

EMERGENCY DOSE: The dose received during a maximum solar flare under emergency conditions. This dose is delivered in 1 day.

Allowed dose = 20 REM

IVA DOSE: The dose received in the permanent lunar shelter. This dose corresponds to the background level on Earth.

Allowed dose = 0 REM

The present flight rules (Table 3) are based upon long term carcinogenic effects, and are below immediate biologically detectable levels with the exception of possible subtle blood changes when the exposure is under terrestrial conditions. In the past, for short duration flights where radiation exposure up to 25 REM was possible or for extended duration missions where little radiation exposure was expected, the acute effects of radiation were not considered. In the case of lunar colonization, radiation exposure can occur after an extended period of living under conditions of one fifth gravity, and the breathing atmosphere may not be the same as that on Earth. There may be other factors in the lunar environment, which can affect radiation susceptibility. These factors may reduce the threshold of acute radiation syndrome, and thus the proposed emergency exposure limits are postulated to preclude any acute radiation symptoms. The long term carcinogenic effects will probably not be changed.

Acute radiation effects are rate dependent. Nearly all the available data on acute effects are derived from the atomic bomb casualties in Japan. In these cases the dose was received instantaneously. When the dose is delivered over an extended period, its biological effect is reduced. The total allowed 25 REM delivered at a constant rate over the 180 day mission will probably not produce any detectable physiological effect. However, if the same dose were delivered in one day, as might occur during a solar flare late in the mission, some acute radiation symptoms might be shown. The atomic bomb doses were delivered to survivors primarily from gamma rays and were deposited nearly uniformly in all parts of the body, but in the case of exposure to solar flare radiation under lightly shielded conditions, the dose decreases rapidly with depth in the body. Under heavier shielding this variation with depth is reduced and approaches the distribution from gamma rays.

Table 3, NASA - Johnson Space Center Flight Rules

R RULE

## MANAGEMENT

14-10 CRIME

14-10 CREW RADIATION EXPOSURE LIMITS

THE FOLLOWING OPERATIONAL CREW IONIZING RADIATION EXPOSURE LIMITS WILL BE ADHERED TO:

EXPOSURE LIMITS (REM)

| CONSTRAINT | DEPTH (5 CM) | EYE (0.3 MM) | SKIN (0.01 CM) |
|---|---|---|---|
| 30 DAY | 25 | 100 | 150 |
| ANNUAL | 50 | 200 | 300 |
| CAREER | 100 - 400* | 400 | 600 |

MALE - *200 + 7.5 (AGE - 30) REM, UP TO 400 REM MAXIMUM
FEMALE - *200 + 7.5 (AGE - 38) REM, UP TO 400 REM MAXIMUM

*STS crew radiation exposure limits were recommended to NASA by the National Council on Radiation Protection and Measurements in 1987 and are expected to be legally adopted as the Agency's Supplementary Standard for compliance with 29 CFR 1960.18. STS flights are nominally constrained to the 30-day exposure limits, which are conservatively set to preclude any mission impact. (Rule 14-6 reference)*

14-11 UNCONFIRMED ARTIFICIAL EVENT

FOR ALL FLIGHT PHASES AND PRELAUNCH, IF AN ARTIFICIAL EVENT IS UNCONFIRMED, THE FLIGHT DIRECTOR WILL BE NOTIFIED AND CONFIRMATION WILL BE PURSUED FROM ALL DATA SOURCES.

*No action is required other than notification of the Flight Director since the predicted or reported event may not be real.*

Table 4 from reference 1, and Table 5 from reference 7 show the radiation symptoms which can be expected under terrestrial conditions for short duration exposures. Figure 8, from reference 8, shows the effect on platelet count at exposures of 69 and 175 RAD over a longer period of time to people on the Marshall Islands due to fallout. The accompanying note indicates that bleeding can be a serious problem when the platelet count drops to 50 percent of normal. Since this was gamma radiation, for which the RBE is unity by definition, the RAD and REM doses are equal.

The limited data of Figure 8 were combined with the typical exposure for radiation treatment of Leukemia (~ 1,000 REM) and the zero dose point to estimate the percent reduction of platelets versus radiation dose delivered in one day or less. It was assumed that the number platelet forming cells that are still living after a radiation exposure are an exponential function of dose. The percentage of reduction can then be written as

$$P(D) = 100\,(1-e^{-kD}) \tag{8}$$

Where:

P(D) is the percent reduction in platelet count after receiving a dose of D (REM)

k is a characteristic constant

D is dose in REM

Using the zero dose and the data for the Marshall Islands in Table 8, in Figure 9, the upper and lower bound curves of the percent reduction of platelets were estimated. The data for the Oak Ridge exposures fall inside these boundaries. Based upon this very limited data, it is estimated that the proposed emergency dose limit of 20 REM will reduce the platelet count from 7.8 to 19.9 percent. The crewman should be considered "burned out" after such an exposure, and should not be further exposed to radiation for the duration of the mission. Every effort should be made to preclude emergency exposures.

For emergency exposures, which are well below the emergency limit, based on Figure 8, a recovery period of 40 to 50 days should be used before reexposure to radiation.

In summary, for purposes of this study a total dose of 25 REM is used, but most of this dose will be reserved for emergency exposure conditions. The emergency dose limits for protracted occupancy of the moon are based upon precluding acute radiation symptoms

## Table 4, Early Effects of Acute Radiation Exposure [a]

(Dose in REM absorbed in 1 day or less)

| Effect | $ED_{10}$ [b] | $ED_{50}$ | $ED_{90}$ |
|---|---|---|---|
| Anorexia | 40 | 100 | 240 |
| Nausea | 50 | 170 | 320 |
| Vomiting | 60 | 215 | 380 |
| Diarrhea | 90 | 240 | 390 |
| Death<br>(20 - 60 days) | 220 | 285 | 350 |

[a] Exposure for a duration of 1 day or less to blood forming organs (greater than or equal to 5 cm tissue depth)

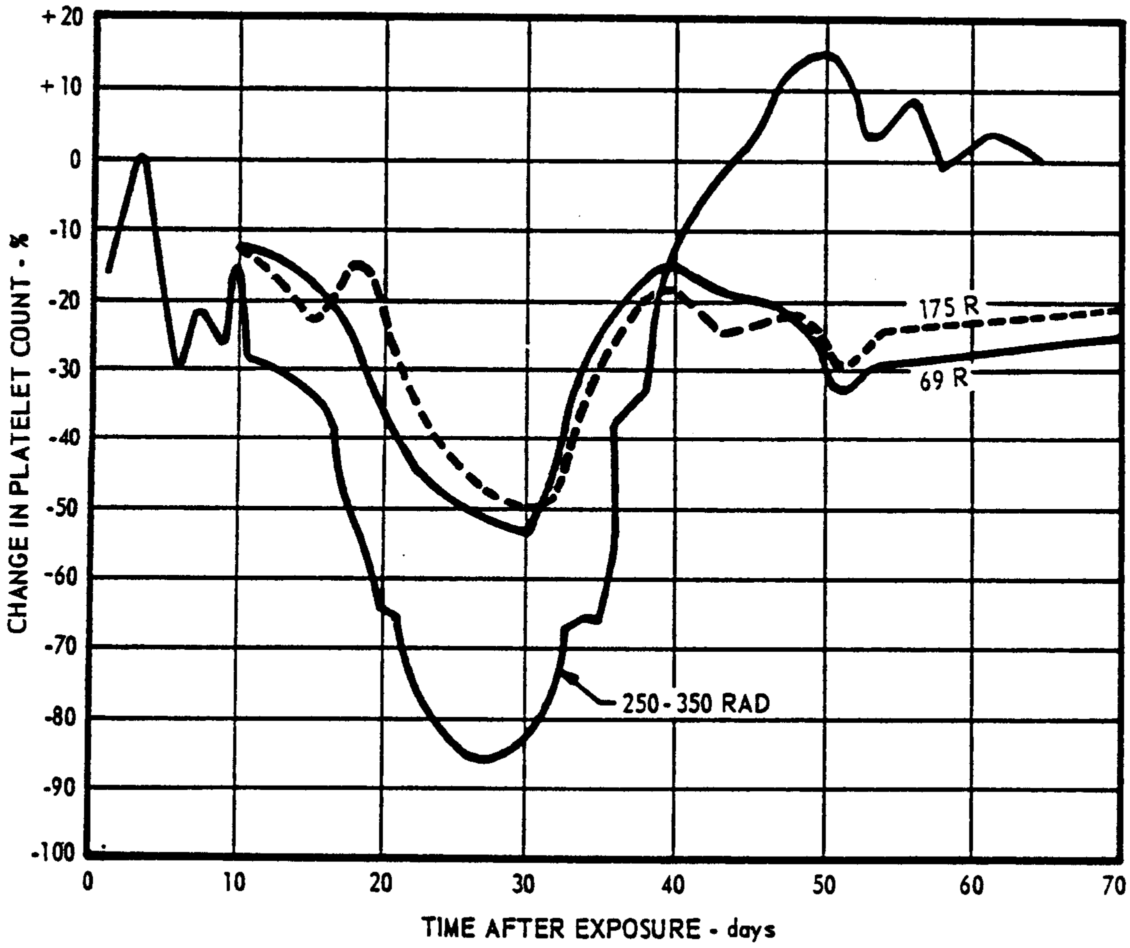
[b] Effective dose for 10, 50, or 90% of a population or normal people to have the indicated physiological effect.

* NOTE: Table was recreated from SCC 86-02 from Severn Communications Corp.

Table 5, Expected Effects from Acute Whole - Body Radiation

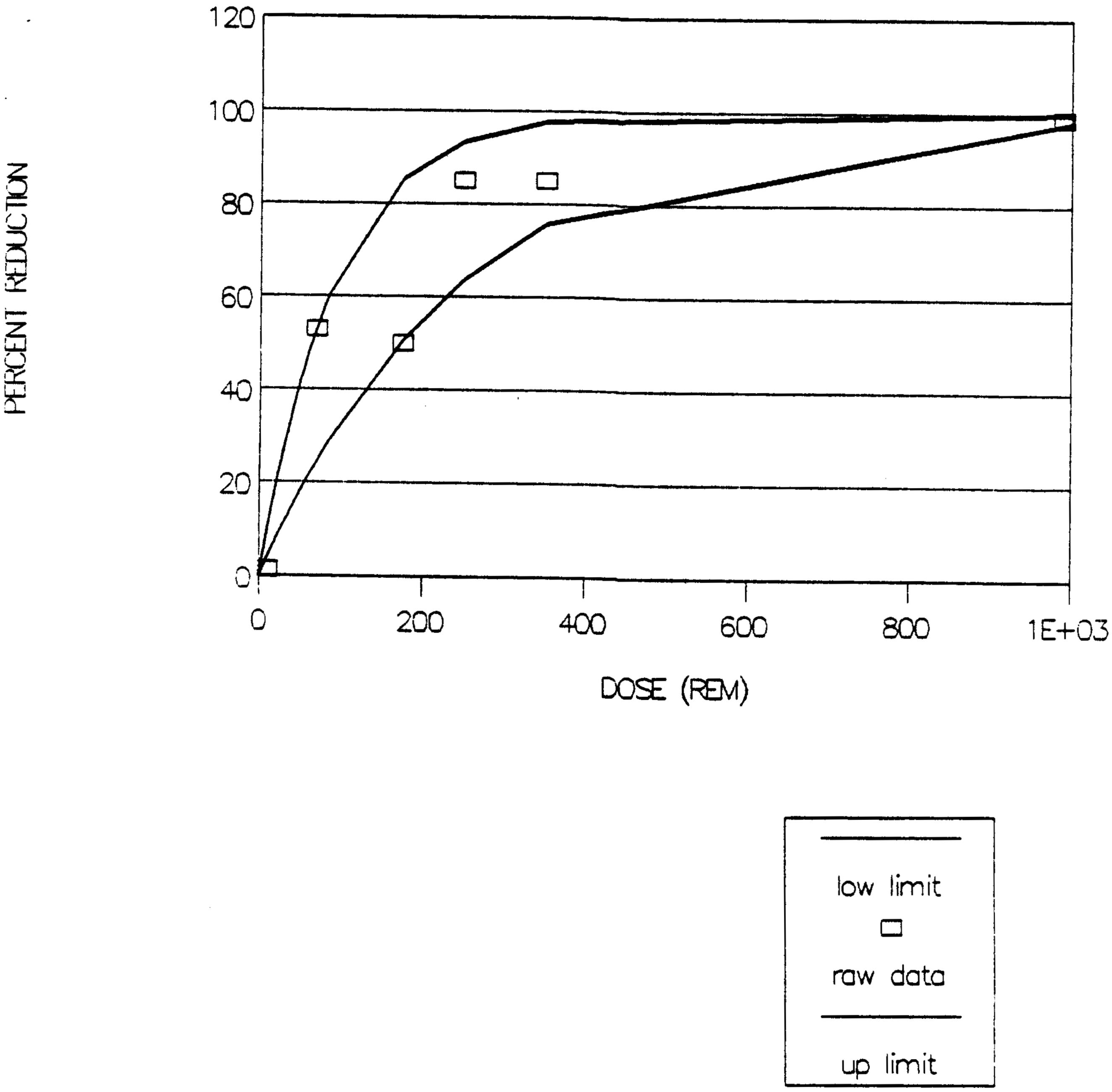
| Dose in Rads | Probable Effect |
|---|---|
| 0 to 50 | No obvious effect, except (possibly) minor blood changes. |
| 50 to 100 | Vomiting and nausea for about 1 day in 5 to 10% of exposed personnel. Fatigue, but no serious disability. Transient reduction in lymphocytes and neutrophilis. |
| 100 to 200 | Vomiting and nausea for about 1 day, followed by other symptoms of radiation sickness in about 25 to 50% of personnel. No deaths anticipated. A reduction of approximately 50% in lymphocytes and neutrophilis will occur. |
| 200 to 350 | Vomiting and nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness, e.g., loss of appetite, diarrhea, minor hemorrhage. About 20% deaths within 2 to 6 weeks after exposure; survivors convalescent for about 3 months. |
| 350 to 550 | Vomiting and nausea in most personnel on first day, followed by other symptoms of radiation sickness, e.g., fever, hemorrhage, diarrhea, emaciation. About 50% deaths within 1 month; survivors convalescent for about 6 months. |
| 550 to 750 | Vomiting and nausea, or at least nausea, in all personnel within four hours from exposure, followed by severe symptoms of radiation sickness, as above. Up to 100% deaths; few survivors convalescent for about six months. |
| 1000 | Vomiting and nausea in all personnel within 1 to 2 hours. Probably no survivors from radiation sickness. |
| 5000 | Incapacitation almost immediately (several hours). All personnel will be fatalities within one week. |

Figure 8, Radiation Effects on Platelets (Ref. 8)



The observed course of platelet counts in adults is shown following the accidental exposure to 69 RAD and 175 RAD from gamma radiation in fall out (Marshall Island Cases), and to 250-300 RAD from a mixture of fast neutrons and gamma rays (Y-12 cases at Oak Ridge).

Figure 9, Estimated Platelet Reduction Vs. Dose



produced under lunar conditions rather than carcinogenic effects, which are the basis of the present terrestrial exposure limits.

For EVA operations there are two conditions under which radiation exposure can occur:

1) Exposure in the spacesuit. The duration of the expendables under these conditions is about 6 hours, and assuming a non-enclosed lunar rover is in use, the maximum time to return to the lunar base is 3 hours.

2) Exposure in a lightly shielded surface vehicle, which has an expandable duration of up to 50 days. The return of this vehicle to the lunar base is longer than the duration of a flare. Rescue from distant points using a flight vehicle is estimated to require about 8 hours.

In the case of the EVA and transit dose there are two sources of radiation exposure which cannot be avoided: transit through the trapped radiation region and Galactic Cosmic Ray exposure. The dose rates per day for the Apollo Missions are considered representative of the expected dose in transit to and from the Moon and lunar EVA.

The data for U. S. spaceflights for the Apollo Missions are shown in Table 6 from reference 9. The dose rates from galactic cosmic rays require complicated computer codes to account for the generation of secondary particles, which are produced at a much higher rate by galactic cosmic rays than by solar protons. Figure 10 shows the cascade of secondary particles, generated by primary particles of energy greater than 300 Mev, which must be traced through a shield in order to determine the dose. In Reference 1 the REM dose vs thickness of aluminum for Galactic Cosmic Rays were reported, and is shown in Figure 11.

The establishment and use of the lunar base will require crewmen to perform EVA, and during such operations they are essentially unshielded. Intravehicular Activity (IVA) before a permanent lunar shelter is established or a storm shelter is delivered will be in vehicles of light shielding, which is assumed to be 5 $gm/cm^2$. When a permanent base is established, massive shielding will reduce the IVA dose to zero, but the EVA dose remains unchanged. As can be seen in Figure 11, the dose rates in the unshielded or lightly shielded condition vary throughout the solar cycle. In Table 7 this data has been used to project the estimated doses during solar maximum, solar minimum, and the average solar state. The measured Apollo dose rates have been included to compare the dose over similar periods. Doses in reference 1 are reported in REM, but the RBE was not reported.

In Table 8 the expected dose from Galactic Cosmic Rays under various shielding conditions and various mission durations are estimated, and observed Apollo doses have been extrapolated to identical mission durations. The Apollo shielding conditions are comparable to the lightly shielded IVA structure (Case 1 of Table 8).

Table 8 indicates that during periods of solar calm, after a permanent shielded lunar base is in place, the amount of EVA activity could be increased by at least a factor of 2 to 3 without exceeding the proposed dose limits.

The emergency dose limits of 20 REM are expected to be received in a relatively short period of time. Because of potential synergism between radiation dose and other features of the lunar environment, a more detailed review by medical authorities may indicate that this limit will be reduced.

The permanent lunar base is assumed to be so heavily shielded that it provides a radiation environment similar to that on Earth away from any man made radiation sources.

Table 6, Dosimetry Data From U.S. Manned Spaceflights (Ref. 9)

| Flight | Duration (hrs/days) | Inclination (deg) | Apogee-Perigee (km) | Average dose (mrad) | Average dose rate (mrad/day) |
|---|---|---|---|---|---|
| Gemini 4 | 97.3 hrs | 32.5 | 296 - 166 | 46 | 11 |
| Gemini 6 | 25.3 hrs | 28.9 | 311 - 283 | 25 | 23 |
| Apollo 7* | 260.1 hrs | | | 160 | 15 |
| Apollo 8 | 147.0 hrs | | lunar orbital flight | 160 | 26 |
| Apollo 9 | 241.0 hrs | | | 200 | 20 |
| Apollo 10 | 192.0 hrs | | lunar orbital flight | 480 | 60 |
| Apollo 11 | 194.0 hrs | | lunar orbital flight | 180 | 22 |
| Apollo 12 | 244.5 hrs | | lunar orbital flight | 580 | 57 |
| Apollo 13 | 142.9 hrs | | lunar orbital flight | 240 | 40 |
| Apollo 14 | 216.0 hrs | | lunar orbital flight | 1140 | 127 |
| Apollo 15 | 295.0 hrs | | lunar orbital flight | 300 | 24 |
| Apollo 16 | 265.8 hrs | | lunar orbital flight | 510 | 46 |
| Apollo 17 | 301.8 hrs | | lunar orbital flight | 550 | 44 |
| Skylab 2** | 28 days | 50 | altitude ≈ 435 | 1596 | 57 ± 3 |
| Skylab 3 | 59 days | 50 | altitude ≈ 435 | 3835 | 65 ± 5 |
| Skylab 4 | 90 days | 50 | altitude ≈ 435 | 7740 | 86 ± 9 |
| Apollo-Soyuz Test Project | 9 days | 50 | altitude ≈ 220 | 106 | 12 |
| STS-1*** | 34 hrs | 38 | altitude ≈ 140 | 12.6 | 8.9 |
| STS-2 | 57.5 hrs | 38 | altitude ≈ 240 | 12.5 ± 1.8 | 5.2 |
| STS-3 | 194.5 hrs | 38 | altitude ≈ 240 | 52.5 ± 1.8 | 6.5 |
| STS-4 | 169.1 hrs | 28.5 | altitude ≈ 297 | 44.6 ± 1.1 | 6.3 |
| STS-5 | 120.1 hrs | 28.5 | altitude ≈ 297 | 27.8 ± 2.5 | 5.6 |
| STS-6 | 120.0 hrs | 28.5 | altitude ≈ 284 | 27.3 ± 0.9 | 5.5 |
| STS-7 | 143.0 hrs | 28.5 | altitude ≈ 297 | 34.8 ± 2.3 | 5.8 |
| STS-8 | 70/75 hrs | 28.5 | altitude ≈297/222 | 35.7 ± 1.5 | 5.9 |
| STS-9† | 240.0 hrs | 57 | altitude ≈ 241 | 103.2 ± 3.1 | 10.3 |
| STS-41B | 191.0 hrs | 28.5 | altitude ≈ 297 | 43.6 ± 1.8 | 5.5 |
| STS-41C | 168.0 hrs | 28.5 | altitude ≈ 519 | 403.0 ±12.0 | 57.6 |

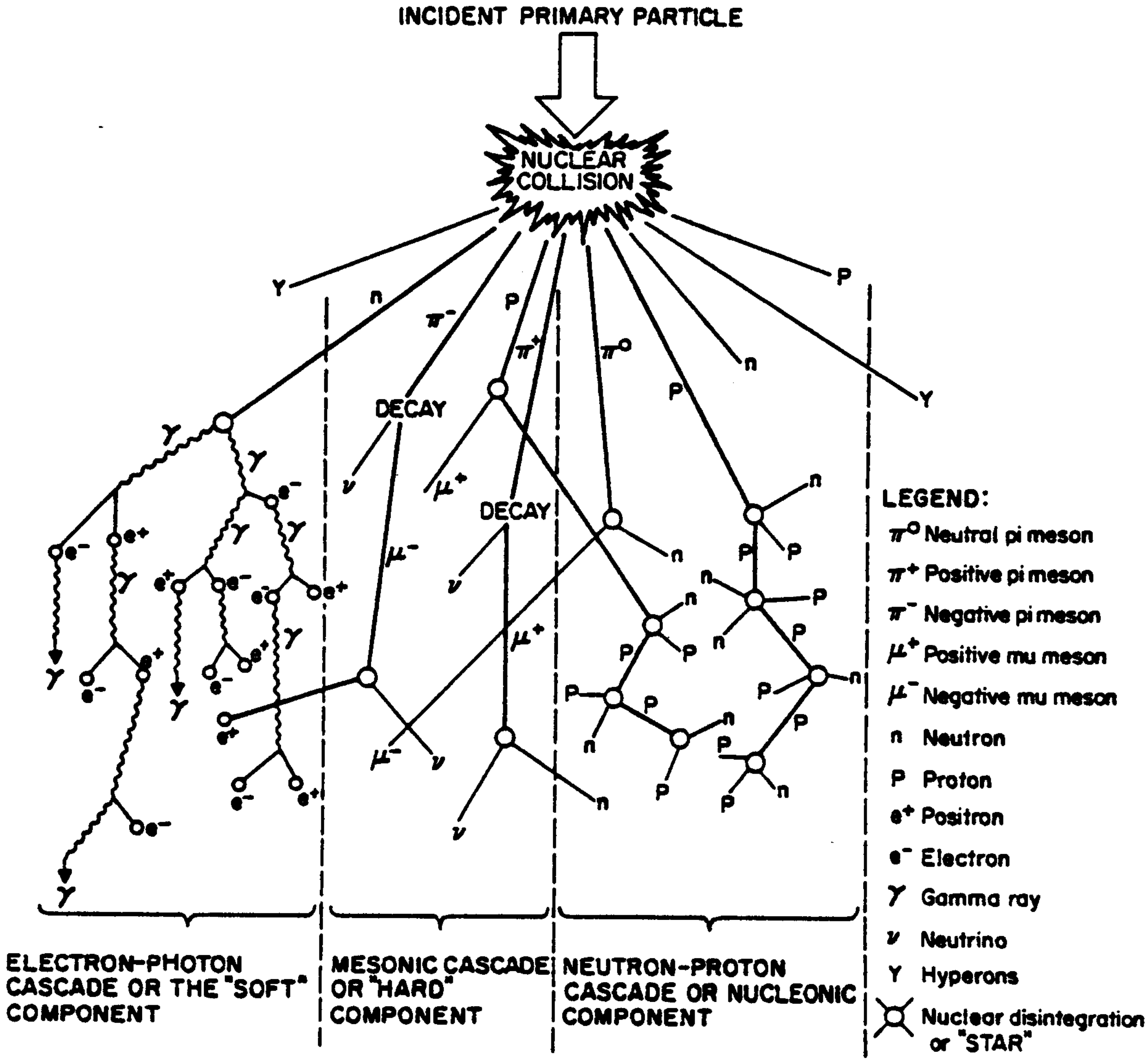
*Doses for the Apollo flights are skin TLD doses. The doses to the blood-forming organs are approximately 40 percent lower than the values measured at the body surface.

**Mean TLD dose rates from crew dosimeters.

***STS-1 data are from an active dosimeter; all other STS data are averages of USF TLD-700 ($^7$LiF) readings from the Area Passive Dosimeter.

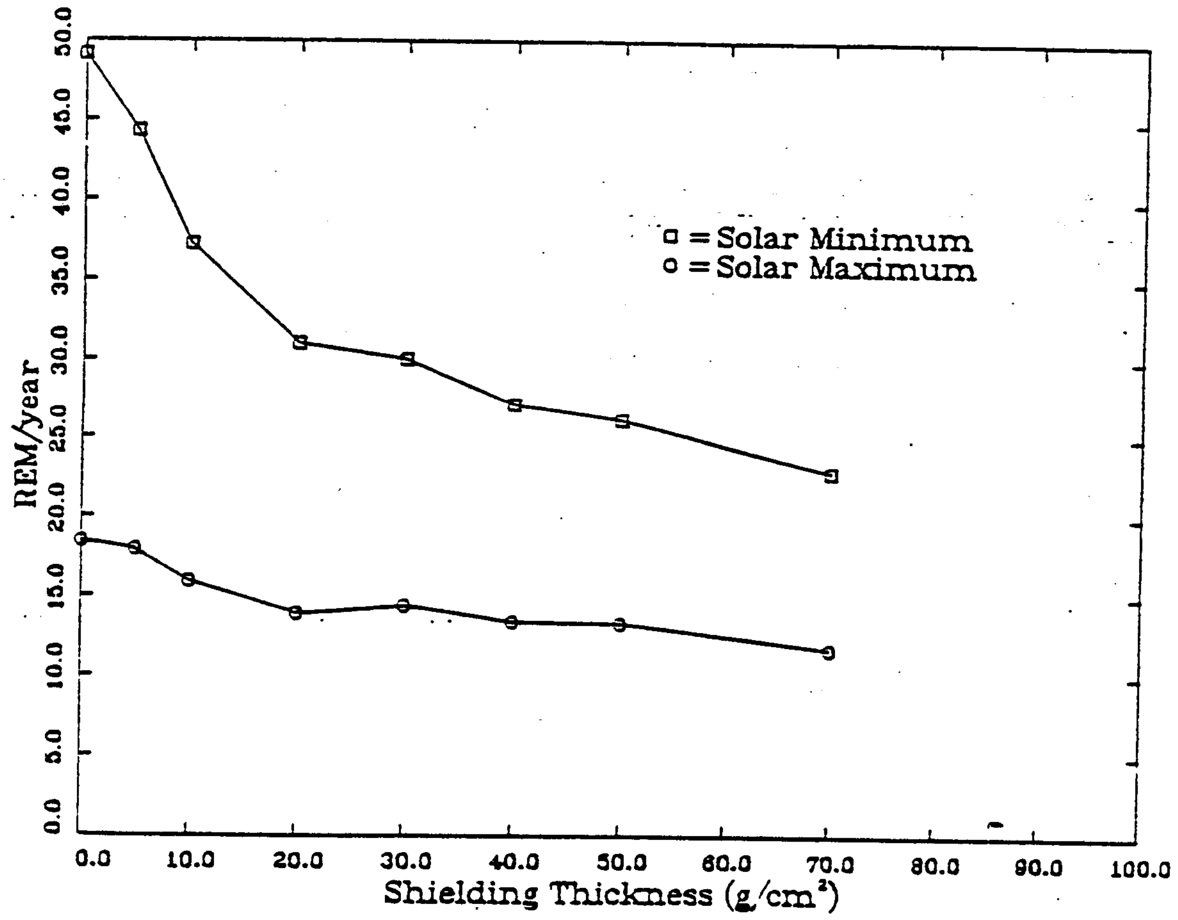
†Spacelab (SL-1).

Figure 10, Creation of Secondary Particles by Galactic Cosmic Rays



When a primary particle with an energy of 300 mev or greater hits a nucleus of target material, secondary particles and electromagnetic radiations are generated in great variety, as shown in this diagram.

Figure 11, Galactic Cosmic Radiation Total Dose, Aluminum Shielding (Reference 1)



Total dose equivalent from galactic cosmic radiation versus shielding thickness in aluminum at solar minimum and solar maximum. 5 g/cm$^2$ body self-shielding is included in addition to the shielding thickness shown.

## Table 7

## Estimate of Galactic Cosmic Ray Dose For Lunar Missions and Comparison to Observed Doses On Apollo Missions

Dose Rates in MREM/DAY from Reference 1

2PI Geometry Factor, 5CM Depth (Blood Forming Organs)

| | Shield Thickness | |
|---|---|---|
| | 0 GM/SQCM | 5 GM/SQCM |
| Solar Min MREM/Day | 65.7 | 60.2 |
| Solar Max MREM/Day | 24.6 | 23.9 |
| Solar Avg. MREM/Day | 45.2 | 42.1 |

Observed Dose Rates On Apollo Missions

Dose Rates in MRAD/Day

| | Skin | BFO* |
|---|---|---|
| Minimum | 20 | 12 |
| Maximum | 60 | 36 |
| Average | 40 | 24 |

Note: Apollo Missions were during the declining period of Cycle 20, and are comparable to calculated average conditions. Apollo 14 Data not included.

* Blood forming organs

Table 8, Calculated Exposures for Various Mission Durations at Various Times in Solar Cycle

CASE 1: LIGHTLY SHIELDED IVA STRUCTURE (5 GM/SQCM)
EVA SHIELDING 0/GM/SQCM EVA TIME 0.1 OF TOTAL

| MISSION LENGTH | 8 DAYS | 24 DAYS | 180 DAYS |
|---|---|---|---|
| SOLAR MIN (MREM) | 486 | 1458 | 10935 |
| SOLAR MAX (MREM) | 192 | 575 | 4315 |
| SOLAR AVG. (MREM) | 339 | 1018 | 7634 |

CASE 2: HEAVILY SHIELDED IVA STRUCTURE (DOSE =0)
EVA SHIELDING 0/GM/SQCM EVA TIME 0.1 OF TOTAL

| MISSION LENGTH | 8 DAYS | 24 DAYS | 180 DAYS |
|---|---|---|---|
| SOLAR MIN (MREM) | 53 | 158 | 1183 |
| SOLAR MAX (MREM) | 20 | 59 | 443 |
| SOLAR AVG. (MREM) | 36 | 108 | 814 |

CASE 3: COMPARABLE APOLLO DATA APPLICABLE TO LIGHTLY SHIELDED CONDITION ABOVE

RANGE OF DOSE FOR EQUAL MISSION PERIODS BASED UPON OBSERVED APOLLO DATA.

SKIN DOSE

| MISSION LENGTH | 8 DAYS | 24 DAYS | 180 DAYS |
|---|---|---|---|
| LOWEST DOSE (MRAD) | 160 | 480 | 3600 |
| AVERAGE DOSE (MRAD) | 320 | 960 | 7200 |
| HIGHEST DOSE (MRAD) | 480 | 1440 | 10800 |

BLOOD FORMING ORGANS (EXTROPOLATED)

| MISSION LENGTH | 8 DAYS | 24 DAYS | 180 DAYS |
|---|---|---|---|
| LOWEST DOSE (MRAD) | 96 | 288 | 2160 |
| AVERAGE DOSE (MRAD) | 192 | 576 | 4320 |
| HIGHEST DOSE (MRAD) | 288 | 864 | 6480 |

NOTE: THE APOLLO DATA WAS MEASURED DURING THE DECLINING PERIOD OF CYCLE 30. RESULTS SHOULD BE COMPARED TO THE AVERAGE CALCULATED CASE.
DOSE RATIO BFO/SKIN PER REFERENCE 9

# 5.0 SHIELDING AND DOSE CALCULATIONS

## 5.1 GALACTIC COSMIC RAYS

As has been shown in the preceding section of this report the calculation of the dose from Galactic Cosmic Rays is complex and involves the slowing down of heavy ions in a given material. The slowing down process produces nuclear fragments, secondary protons, mesons, gamma rays, and neutrons. These secondary particles must be traced through the shielding. The dose delivered is a summation of the energy deposited by each of the various type of particles, RAD dose, times its RBE factor = REM dose. The composition and energy of the particles will depend upon the material in which they are attenuated. In general, the lower the atomic number, the lower the generation of secondary particles. As can be seen in Figure 10 from Reference 1, shielding up to 70 $gm/cm^2$ reduces the dose at solar maximum by only 20 percent; thus massive shielding is required to eliminate the dose from Galactic Cosmic Rays.

On Earth the atmosphere provides shielding from galactic cosmic rays. Atmospheric pressure of 750 millibars (the pressure at around 9000 ft altitude, the reasonable upper limit at which people live) corresponds to a shield of 750 $gm/cm^2$, made up principally of oxygen and nitrogen. The atmosphere's atomic number (a measure of yield of secondaries) ranges between 7 and 8. This level of shielding on the lunar surface can be considered the equivalent of the dose received on Earth, which is normally not added into the exposure dose of an individual. To provide equivalent shielding on the lunar surface one is faced with two choices:

1) Transporting the material from Earth, which has the advantage of allowing the choice of a low atomic number material, but with very high transportation cost.

2) Using naturally occurring material from the lunar surface or materials created as byproducts of production of materials from lunar materials. In this case the most commonly occurring material is silica with atomic numbers between 8 and 14. The yield of secondaries in silica may have to be somewhat higher than that in air, hence shielding mass per unit area may be greater than that provided by the Earth's atmosphere.

## 5.2 SOLAR FLARE SHIELDING

The composition of the solar flare particles is principally protons, which have spectral energy distributions lower than those of galactic cosmic rays. Fewer secondary particles are generated, and the secondary particles can be accounted for by a buildup factor, a correction factor applied to the dose delivered by primary particles for shields of moderate thickness. A qualitative description of the steps in calculating the required shielding thickness when the exact configuration of the spacecraft is known is as follows. First the integral energy spectrum described in the environmental section is divided into energy increments. Some point on the crewman's body is taken as the point at which the dose is to be determined. Ray traces are made through 4 pi of solid angle from that point, and the thickness of each material within each increment of solid angle is determined. For each energy increment and each increment of solid angle the dose is determined as will be described later, and the results summed to establish the total dose.

A charged particle is slowed by producing ionization in the material it traverses or by a nuclear collision, which produces secondary particles, which again dissipate their energy by ionization. The amount of energy lost in passing through one gram of material, which has a frontal area of one square centimeter, is called the Stopping Power. Note that in this definition the unit of thickness is grams per $cm^2$, or density times thickness. Stopping Power is proportional to the square of the charge being stopped, and varies with the energy of the particle traversing the stopping material. The amount of energy required to produce ionization is greatest in materials of low atomic number and decreases with increasing atomic number. Thus materials of low atomic number are the most effective shielding materials based upon the unit of grams per $cm^2$, but because these materials are, in the majority of cases, of lower density than those of higher atomic number, their thickness in centimeters or other linear unit may exceed that of the higher atomic number materials.

For the case in which the particles produce only ionization, monoenergetic particles are all stopped by the same thickness ($gms/cm^2$) of material, which is referred to as the Range in that material. The Range (R) of a particular charged particle can written in terms of the energy (E) of the particle as:

$$R(E) = AE^n \qquad (9)$$

This equation is valid for thicknesses of up to 20 grams/cm$^2$ and energies from 10 to about 250 Mev to within about 5 percent. A is a constant for each stopping material, n is a constant for all materials and has a value of 1.78 (Reference 11).
Note that this equation is of the same form as Equation 1.

The Stopping power can be determined from this equation. Differentiating Equation 8:

$$dR/dE = nAE^{n-1} \qquad (10)$$

This is the range lost when a particle gives up dE of energy. The energy lost in an interval dR is the reciprocal of the value in Equation 10. Since dR is a range loss, a negative value of the reciprocal is taken and by definition this is the stopping power.

$$S(E) = -1/dR/dE = -(1/nA)E^{1-n} \qquad (11)$$

In passing through a selected volume of tissue the Stopping Power determines the amount of energy deposited in the tissue. Converting the energy from Mev to hundreds of ergs (multiply by 1.66 x $10^{-8}$) determines the RAD dose and multiplying by a relative biological factor (RBE) establishes the REM dose. The energy of a particle exiting a shield of thickness X is established from the incident particle energy by manipulation of equation 8 as follows:

$$X = R(E_i) - R(E_x) \qquad (12)$$

$$X = AE_i^n - AE_x^n \qquad (12a)$$

$$E_x = (E^n_i - X/A)^{1/n} \qquad E_i > (X/A)^{1/n} \qquad (12b)$$

$$E_x = 0 \qquad E_i < X/A$$

The simple exponent form of the energy-range relationships in Equation 8 have been extended to the range of 5 to 1200 Mev in reference 11 by curve fitting, which results in equations as follows:

$$R(E) = (a/2b)\ln(1+2bE^{n}) \qquad (13)$$

$$S(E) = -(1/an)E^{1-n}+(2b/an)E \qquad (14)$$

$$n = 1.78$$

The coefficients a and b vary with atomic number, Z, and a list of several materials were given in reference 11. The variation of a and b were fitted to polynomials, which reproduce the values in reference 11 with an error of less than 1 percent with the following equations:

$$a = 1.65591 + 1.37754 \times 10^{-1Z} - 5.16973 \times 10^{-3}Z^{2} + 8.60948\times10^{-5}Z^{3} \qquad (15)$$

and

$$b = 1.67000 + 1.82981 \times 10^{-2}Z + 1.241099 \times 10^{-2}Z^{2} -9.0232 \times 10^{-4}Z^{3} + 1.817724 \times 10^{-5}Z^{4} \qquad (16)$$

This fit applies to atomic numbers, Z, less than 20. Slightly different values of a, b, and n apply to atomic numbers above 20, but since all the materials in this report have Z less than 20 no fit was made for these materials. Values of range can be computed using equations 13, 14, and 15, and these ranges can be used to determine the ratio of shielding thickness for various materials (See Appendix B).

Correction terms are needed to account for the loss of primary protons due to inelastic collisions with the nuclei of the shielding material. A term to account for the secondary particles is needed to complete a dose calculation (See reference 11 for a treatment of these terms).

Numerical integration is used to calculate the total primary dose at a given point where diverse materials are encountered at different solid angle directions. The spectrum of the incident solar flare is broken down into a series of energy intervals; the spectrum is traced through the various layers of material encountered and the dose from the exiting spectrum from each energy interval is summed over all energies and all solid angles to establish the total primary dose. A second calculation can be carried out to determine the amount of secondary particles generated in the shielding volume. This calculation involves knowing the reaction cross sections for producing particles and performing a Monte Carlo type calculation to establish the particles generated and the dose delivered by these particles. However, in practice, this dose contribution can be incorporated into the primary dose by a correction factor.

An analytical expression was shown in reference 11 which will take into account multiple shielding materials along one ray path, and this permits the calculation of a monodirectional source and a slab shield, or the dose at the center of a spherical shield. A similar analytical expression in reference 12 for the case of an isotropic source incident on a slab shield can be modified and used for dose calculations. This latter form is required for dose points not at the center of a sphere.

The preceding paragraphs show the type of calculations required to perform detailed shielding thickness calculations for a known structure when the details of the structure have been determined. For establishing initial requirements a quick method of estimating solar flare dose under EVA conditions and an estimate of emergency shelter shielding thickness mass and volume are required to establish an overall approach to dose control. There are two conditions, which need to be considered:

1) When performing EVA operations with essentially no shielding or in a lightly shielded vehicle, what is the dose rate? Estimates of this kind give some idea of the time available to make a retreat to the permanent lunar base.

2) If retreat to the permanent lunar base is not an option, what shielding thickness is required to limit the dose in a storm shelter to the emergency limits?

Various authors have calculated the dose received at the center of a spherical shelter with aluminum shielding from a variety of solar flares of varying spectra. To provide the EVA dose rate two sets of data were combined to give the dose rate estimates shown in Table 2. The first was the dose from a solar flare behind aluminum shielding for a flare with a characteristic rigidity of 80 shown in reference 11. The second, reference 13, shows the ratio of the normalized skin dose to the dose at a thickness of tissue from 0 to 35 gm/cm$^2$ for spectra with characteristic rigidities of from 80 to 195. From reference 11, the dose at 5 gm/cm$^2$ was used to calculate the dose per unit flux at that depth (i.e. the dose to the blood forming organs). From the data in reference 13, a plot on log paper at a constant shield thickness of the ratio of skin dose to 5 gm/cm$^2$ versus characteristic rigidity indicated that the ratio was approximately linear. The data from this was used to modify the dose per unit flux for N(>30Mev)/cm$^2$ and for a characteristic rigidity of 80 to other characteristic rigidities. This method is approximate, since the variation in skin dose with spectral variation is not taken into account. However, since the shielding afforded by the space suit and its associated backpack are not known it does provide a conservative estimate of the dose rate. In Table 2 the crewman is assumed to be on a flat plane so that radiation is received from 2 pi steradians.

To provide estimates of the shielding required to protect for the maximum solar event in an emergency shelter, the dose per unit flux for a flare expressed as a power function of energy (Equation 1) with a power of - 3.12 (the value proposed in the model flare in the environment previously discussed) was determined from data in reference 11. A polynomial was then fitted to the log of dose per unit flux as a function of shield thickness. In the environmental section, the model event was given as 1x10$^{10}$ protons/cm$^2$. In the dose section the emergency dose was set at 20 REM. The allowed dose per proton is therefore 2x10$^{-9}$REM per unit flux. The REM dose is estimated as about 1.7 times greater than the RAD dose, (Reference 25) hence the allowed RAD dose is set at 12 RAD. This calculation is equivalent to radiation passing normally through a slab. The configurations of the emergency shielding shelter are conceived as cylindrical or cubical in shape, therefore a calculation of the percent of solid angle subtended by various sections of the cylinder and the end caps of the cylinder can be made if the dose point is on the center line and at the lateral midpoint of the cylinder (See Appendix A). The results of these emergency shelter calculations can be found in Table 9.

## 6.0 CONCEPTUAL DESIGNS FOR RADIATION SHIELDING

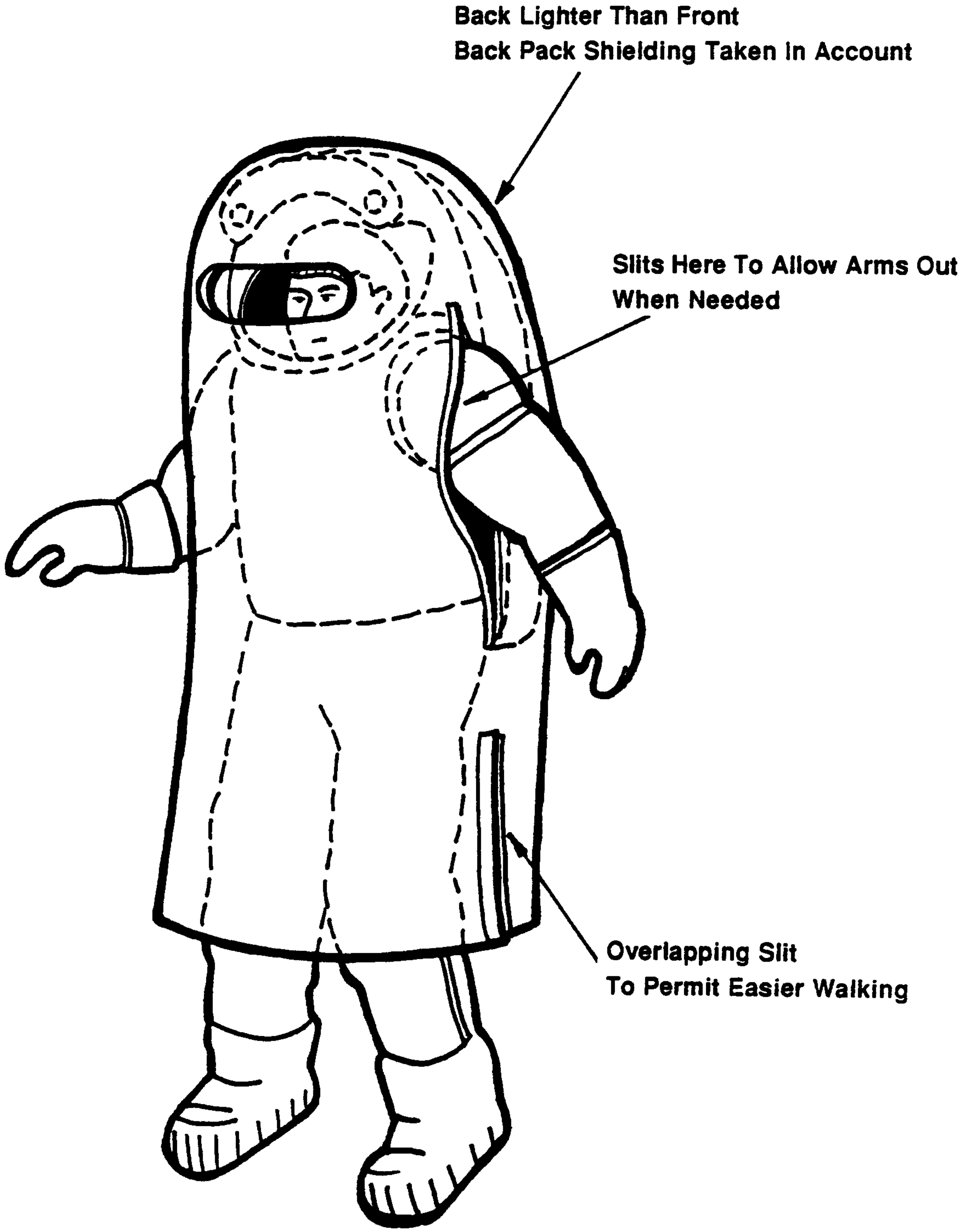
Before the total mass of shielding can be determined the volume protected by shielding must be determined. This volume will depend upon how much work must be performed while in this volume, and the duration of time the crewman must remain in the volume. In the preceding sections of this report it has been established that all IVA operations for missions of 180 days must be performed behind massive shielding (at 0 dose condition) in order to have a sufficient dose cushion to allow EVA operations and a contingency reserve in the event that a solar flare occurs while an EVA operation is being performed at a site remote from the IVA shelter. To establish the allowable dimensions for the protected volume the dimensions of the 99th percentile man as given in reference 14 were used to determine the shelter internal dimensions as follows:

| | |
|---|---|
| Height | 75 inches |
| Shoulder width | 22 inches |
| Sitting height | 39 inches |
| Knee to buttocks | 23.5 inches |
| Feet length | 12 inches (maximum vertical dimension while in prone position) |

### 6.1 PARTIAL PROTECTION GARMENT CONCEPT

Reference 4 has calculated that the RAD dose for the six hour peak of the August 1972 flare in free space under EVA conditions is 123 RAD. Assuming an RBE of 1.15, based upon a thin shield with little thickness in which secondaries can develop and that our model flare is about 10 percent greater than the August event indicates that the model dose rate would be 12 REM/hr. Over the estimated return period of 3 hrs the total dose would be 36 REM or nearly twice the allowed emergency dose. To lower this dose as far as practical a partial protective garment is proposed. A garment that provides 8 gm/cm$^2$ shielding is estimated to reduce the dose rate by about 5 to 7 times compared to the unshielded spacesuit. This would reduce the emergency dose to the range of 5 to 7 REM, which is below the emergency limit. A conceptual sketch is shown in Figure 12.

Figure 12, Partial Protection Garment



The garment is conceived as a sleeveless cloak extending to the knees. A helmet and protection for the neck is also included. A lexan visor provides eye protection. For a crewman in the upper 95 percent of height, 75", and wearing a space suit, if the garment is constructed of carbon fiber cloth weighing 20 oz per square yard and providing 8 $gm/cm^2$ (118 layers about 3 inches thick), the garment is estimated to weigh around 375 pounds, (170 kg) which is the equivalent of 63 pounds under reduced lunar gravity. As the details of the space suit become available some tailoring to reduce the garment thickness where the space suit provides shielding, may reduce this weight. The garment is conceived as providing protection for extending return time to the main lunar base or for performing emergency operations. A trade off between the effects of adding weight to the space suit and mobility to complete required tasks will determine the final weight. As details of the design evolve, it may be possible to substitute polyethylene for some of the layers, thus decreasing garment weight, however bulkness of the polyethylene arrangement may preclude its use. The garment is insufficient to protect the crewman over the entire period of the flare, but since the space suit can provide support for only a few hours this should not be a major issue.

## 6.2 EXTENDED MISSION REQUIREMENT

For the extended mission away from the main base in a vehicle, which provides a shirt sleeve environment, and from which return to the main base would require at least 8 hours, shielding which protects over the entire flare is required. Two designs of this shielding should be considered:

1) If the vehicle is to cover a wide range with no particular fixed point in its itinerary, then the shielding will have to be incorporated into the vehicle.

2) Alternately if the vehicle acts as a "line shack," i.e. remains in a relatively fixed position and is resupplied from a lander or other vehicle, then the shielded volume could be external to the vehicle, which would have the advantage of having to be transported only once to the remote site.

The mass and volume of shielding when integrated into a surface vehicle will seriously limit the capabilities of the vehicle. Operational planning should include concepts for maximum use of terrain to provide shadow shielding such as rilles and cliffs to limit the solid angle from which radiation is received. If caves were available in which the vehicle could take shelter, shadow shielding such as might be provided by a trailer could provide a partial answer to reducing shielding mass. Such a solution could not be expected on every mission. The use of a heat drilled cavern might be considered, but the power and hardware requirements again will seriously degrade the overall vehicle performance. The use of blasting to create a crater has been suggested by several authors, but the time spent in retreating to a safe distance of several kilometers to avoid the damage from the ejecta of the blast by the vehicle handicaps this approach. The warning period of the onset of a solar flare will not exceed three hours, and for vehicles in transit rather than at a semipermanent site, this time will severely limit the time to prepare shielding using materials existing in the immediate area. The warning available for preparing for a flare is probably less than three hours. Avoiding exposure appears to be the best solution to the exploration shielding problem, and three approaches should be considered.

1) A flier or lander on continuous alert to evacuate to a permanent shelter in less than three hours.

2) Use teleoperations and automated equipment to eliminate the requirement for continuous manning of remote sites.

3) Plan operations around the period of low solar activity, which is estimated to exist whenever the sunspot number is below 35.

In the section which follows the volumes and masses together with the systems to support the crewman during the period of a flare are presented to serve as a guide in evaluating whether incorporation of shielding into surface vehicles is achievable.

### 6.2.1 ABSOLUTE MINIMUM CHAMBER

This is the smallest cylinder or hemicylinder which will contain a man. It is considered suitable for use for only periods of a few hours, since movement is so constricted that the crewman is able to perform only very limited movement. The volume for a cylinder, allowing 2 inches in each direction, is 20.2 cubic feet (radius 12 inches length 77 inches). For a hemicylinder, the volume is half this volume or 10.1 cubic feet (allows shoulders and buttocks to be on a flat surface). Note that such a chamber would be internal to a vehicle or shelter since it is too small to allow entry with EVA equipment. It is presented here to show a volume and mass, which are below minimum limits, in order to provide less than achievable limit mass and volume. Table 9 provides volumes, mass, and dimensions for this type of chamber. These chambers hold the dose to 20 REM for the design flare.

### 6.2.2 MINIMUM FUNCTION CHAMBER

These chambers are conceived as being habitable for periods of up to 10 days if solar flare activity were to persist for that long a period. The trade is to achieve habitability, while at the same time minimizing volume and shield mass. To examine these criteria a number of shielded volumes were considered and the mass required to shield these volumes against the model solar event postulated in Section 3.1 was calculated. Volumes and shielding masses are shown in Table 9.

<u>The first configuration</u> examined is a cylinder 20.5 inches in radius and 77 inches long. This cylinder has a habitable volume of 58 cubic feet. The principal disadvantage of this arrangement is the rounded bottom which precludes comfortable occupancy. No position can be assumed by the crewman without resulting in some pressure point and/or cramped or contorted position.

<u>The second configuration</u> was a hemicylinder with a radius of 41 inches and a length of 77 inches. This results in a habitable volume of 117.6 cubic feet. The habitability is markedly improved, but the volume is excessive. Shield mass is approximately 50% greater than the first arrangement.

Table 9, Minimum Function Chambers - Approximate Shield Masses

The shield is based on model flare N(>E) = 4.609*10^14*E^-3.12. For free space (4 pi ster) the following thicknesses apply: Al 63.6 $gm/cm^2$ or 0.82 ft, Carbon 53.4 $gm/cm^2$ or 1.17 ft. For the lunar surface (2pi ster) the following thicknesses apply: Al-58.6 $gm/cm^2$ or 0.725 ft, Carbon 49.2 $gm/cm^2$ or 1.08 ft, Water 44.3 $gm/cm^2$ or 1.45 ft. Dose is calculated at the center of the space. Body self-shielding is not taken into account. Doses at other points in the volume will be different.

| CONFIGURATION | MATERIAL | R(INSIDE) FT | L(INSIDE) FT | V(INSIDE) FT^3 | V(OUT) FT^3 | V(SHIELD) FT^3 | M(SHIELD) TONS |
|---|---|---|---|---|---|---|---|
| ABSOLUTE MINIMUM | AL | 1.00 | 6.41 | 20.10 | 83.88 | 63.78 | 5.27 |
| CYLINDER ONE OCCUPANT | C | 1.00 | 6.41 | 20.10 | 129.15 | 109.05 | 5.10 |
| 4 PI GEOMETRY NO 2 PI | H20 | 1.00 | 6.41 | 20.10 | 199.73 | 179.63 | 5.60 |
| ABSOLUTE MINIMUM | AL | 2.00 | 6.41 | 40.28 | 148.81 | 108.53 | 8.97 |
| HEMICYLINDER ONE OCCUPANT | C | 2.00 | 6.41 | 40.28 | 226.47 | 186.19 | 8.71 |
| 4 PI GEOMETRY | H20 | 2.00 | 6.41 | 40.28 | 348.03 | 307.75 | 9.60 |
| ABSOLUTE MINIMUM | AL | 2.00 | 6.41 | 40.28 | 91.68 | 51.40 | 4.25 |
| HEMICYLINDER ONE OCCUPANT | C | 2.00 | 6.41 | 40.28 | 127.37 | 87.09 | 4.08 |
| 2 PI GEOMETRY | H20 | 2.00 | 6.41 | 40.28 | 174.62 | 134.34 | 4.19 |
| (NO LOWER SHIELD) | | | | | | | |
| MINIMUM FUNCTION | AL | 1.71 | 6.41 | 58.77 | 161.83 | 103.06 | 8.52 |
| CYLINDER ONE OCCUPANT | C | 1.71 | 6.41 | 58.77 | 227.32 | 168.55 | 7.89 |
| 4 PI GEOMETRY NO 2 PI | H20 | 1.71 | 6.41 | 58.77 | 324.57 | 265.80 | 8.29 |
| MINIMUM FUNCTION | AL | 3.42 | 6.41 | 117.54 | 277.45 | 159.91 | 13.22 |
| HEMICYLINDER ONE OCCUPANT | C | 3.42 | 6.41 | 117.54 | 382.43 | 264.89 | 12.40 |
| 4 PI GEOMETRY | H20 | 3.42 | 6.41 | 117.54 | 525.65 | 408.11 | 12.73 |
| MINIMUM FUNCTION | AL | 3.42 | 6.41 | 117.54 | 211.78 | 94.24 | 7.79 |
| HEMICYLINDER ONE OCCUPANT | C | 3.42 | 6.41 | 117.54 | 271.64 | 154.10 | 7.21 |
| 2 PI GEOMETRY | H20 | 3.42 | 6.41 | 117.54 | 347.23 | 229.69 | 7.17 |
| FLAT FLOOR (2 FT WIDE) | AL | 2.00 | 6.41 | 78.23 | 196.47 | 118.25 | 9.78 |
| CYLINDER ONE OCCUPANT | C | 2.00 | 6.41 | 78.23 | 267.81 | 189.58 | 8.87 |
| 4 PI GEOMETRY | H20 | 2.00 | 6.41 | 78.23 | 373.64 | 295.41 | 9.22 |
| FLAT FLOOR (2 FT WIDE) | AL | 2.00 | 6.41 | 78.23 | 162.54 | 84.32 | 6.97 |
| CYLINDER ONE OCCUPANT | C | 2.00 | 6.41 | 78.23 | 219.00 | 140.78 | 6.59 |
| 2 PI GEOMETRY | H20 | 2.00 | 6.41 | 78.23 | 292.37 | 214.14 | 6.68 |

Table 9, Minimum Function Chambers - Approximate Shield Masses (Continued)

MORE THAN ONE OCCUPANT

| CONFIGURATION | MATERIAL | R(INSIDE) FT | L(INSIDE) FT | V(INSIDE) FT^3 | V(OUT) FT^3 | V(SHIELD) FT^3 | M(SHIELD) TONS | VOL/MAN FT^3 | TONS/MAN TONS |
|---|---|---|---|---|---|---|---|---|---|
| 2 MAN HORIZONTAL FLAT FLOOR | AL | 2.00 | 6.41 | 126.05 | 282.98 | 156.94 | 12.98 | 63.02 | 6.49 |
| CYLINDER +CUBIC 2x3.73x6.41 | C | 2.00 | 6.41 | 126.05 | 373.91 | 247.87 | 11.60 | 63.02 | 5.80 |
| 4 PI GEOMETRY | H20 | 2.00 | 6.41 | 126.05 | 505.38 | 379.34 | 11.84 | 63.02 | 5.92 |
| 2 MAN HORIZONTAL FLAT FLOOR | AL | 2.00 | 6.41 | 126.05 | 232.56 | 106.52 | 8.81 | 63.02 | 4.40 |
| CYLINDER +CUBIC 2x3.73x6.41 | C | 2.00 | 6.41 | 126.05 | 301.32 | 175.27 | 8.20 | 63.02 | 4.10 |
| 2 PI GEOMETRY | H20 | 2.00 | 6.41 | 126.05 | 388.95 | 262.90 | 8.20 | 63.02 | 4.10 |
|  |  | RECTANGULAR | CROSS SECTIONS LENGTH 6.41 |  |  |  |  |  |  |
|  |  | WIDTH FT | HEIGHT FT |  |  |  |  |  |  |
| 2 MAN VERTICAL OR HORIZONTAL | AL | 2.00 | 6.84 | 87.69 | 248.74 | 161.05 | 13.32 | 43.84 | 6.66 |
| CUBIC (2W,6.84H,6.41L) | C | 2.00 | 6.84 | 87.69 | 347.98 | 260.29 | 12.18 | 43.84 | 6.09 |
| 4 PI GEOMETRY | H20 | 2.00 | 6.84 | 87.69 | 493.03 | 405.34 | 12.65 | 43.84 | 6.32 |
| 2MAN HORIZONTAL | AL | 4.00 | 3.42 | 87.69 | 233.06 | 145.37 | 12.02 | 43.84 | 6.01 |
| CUBIC (4W,3.42H,6.41L) | C | 4.00 | 3.42 | 87.69 | 339.83 | 252.14 | 11.80 | 43.84 | 5.90 |
| 2 PI GEOMETRY | H20 | 4.00 | 3.42 | 87.69 | 485.20 | 397.51 | 12.40 | 43.84 | 6.20 |
| 2 MAN VERTICAL | AL | 2.00 | 6.84 | 87.69 | 205.14 | 117.45 | 9.71 | 43.84 | 4.86 |
| CUBIC (2W,6.84H,6.41L) | C | 2.00 | 6.84 | 87.69 | 281.65 | 193.96 | 9.08 | 43.84 | 4.54 |
| 2 PI GEOMETRY | H20 | 2.00 | 6.84 | 87.69 | 379.31 | 291.62 | 9.10 | 43.84 | 4.55 |
| 4 MAN VERTICAL & HORIZONTAL | AL | 4.00 | 6.84 | 175.38 | 385.33 | 209.95 | 17.36 | 43.84 | 4.34 |
| CUBIC (4W,6.84H,6.41L) | C | 4.00 | 6.84 | 175.38 | 508.48 | 333.11 | 15.59 | 43.84 | 3.90 |
| 4 PI GEOMETRY | H20 | 4.00 | 6.84 | 175.38 | 684.27 | 508.89 | 15.88 | 43.84 | 3.97 |
| 4 MAN VERT 2 HI BY 2 ACROSS | AL | 4.00 | 6.84 | 175.38 | 324.06 | 148.68 | 12.29 | 43.84 | 3.07 |
| CUBIC (4W,6.84H,6.41L) | C | 4.00 | 6.84 | 175.38 | 417.25 | 241.87 | 11.32 | 43.84 | 2.83 |
| 2 PI GEOMETRY | H20 | 4.00 | 6.84 | 175.38 | 533.87 | 358.50 | 11.19 | 43.84 | 2.80 |
| 3 VERTICAL & 3 HORIZONTAL | AL | 6.00 | 10.44 | 394.60 | 732.37 | 337.77 | 27.93 | 43.84 | 3.10 |
| CUBIC (6x10.44Hx6.41L) | C | 6.00 | 10.44 | 394.60 | 918.33 | 523.73 | 24.51 | 43.84 | 2.72 |
| 4 PI GEOMETRY | H20 | 6.00 | 10.44 | 394.60 | 1175.06 | 780.46 | 24.35 | 43.84 | 2.71 |
| 3 VERTICAL & 3 HORIZONTAL | AL | 6.00 | 10.44 | 394.60 | 644.71 | 250.11 | 20.68 | 43.84 | 2.30 |
| CUBIC (6W,10.44H,6.41L | C | 6.00 | 10.44 | 394.60 | 794.04 | 399.44 | 18.69 | 43.84 | 2.08 |
| 2 PI GEOMETRY | H20 | 6.00 | 10.44 | 394.60 | 975.81 | 581.22 | 18.13 | 43.84 | 2.01 |

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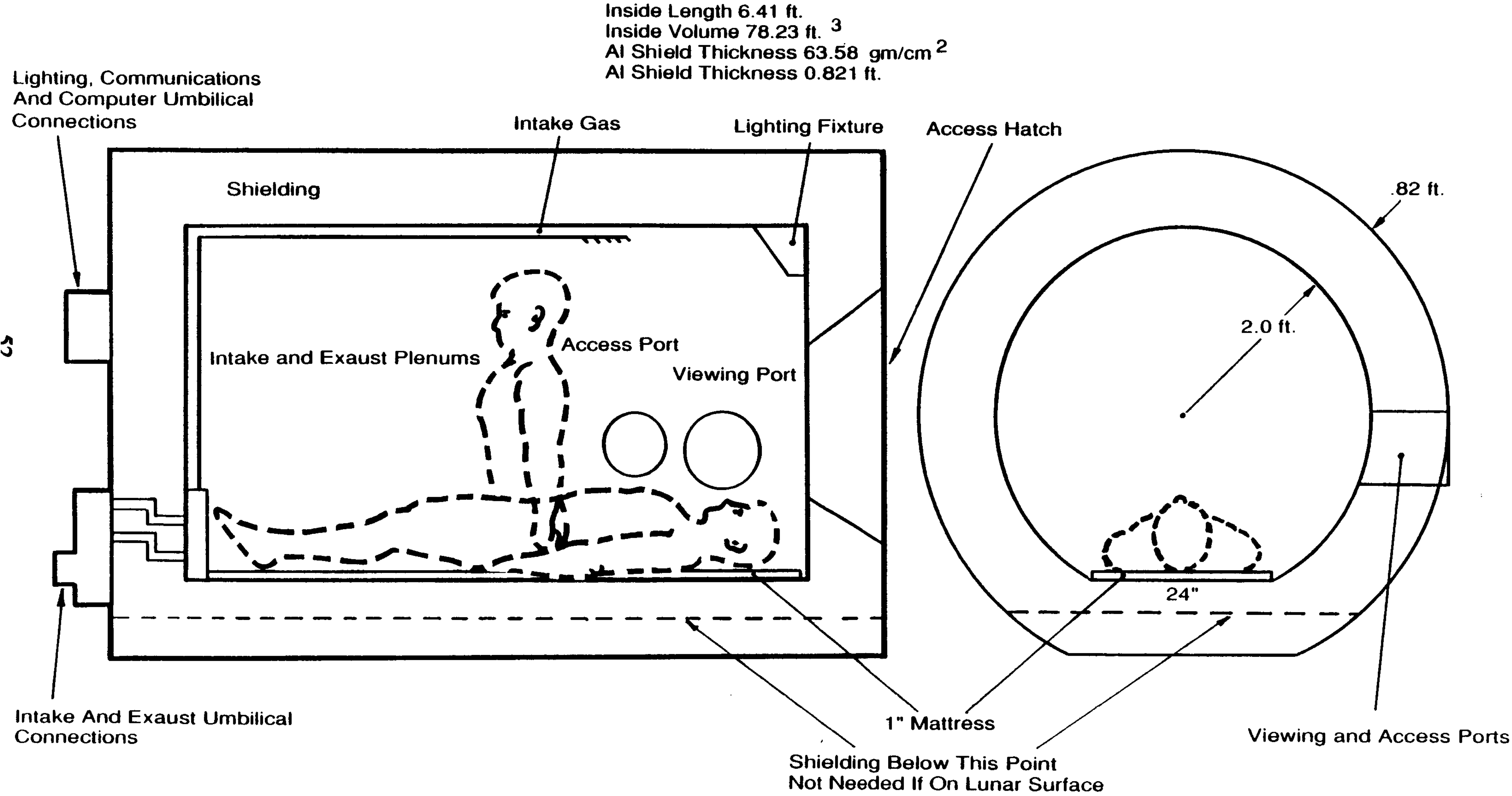
OF POOR QUALITY

Figure 13

# SINGLE OCCUPANT STORM SHELTER



Inside Length 6.41 ft.
Inside Volume 78.23 ft. $^3$
Al Shield Thickness 63.58 gm/cm $^2$
Al Shield Thickness 0.821 ft.

The third configuration is a cylinder with the bottom flattened so that the crewman can lie comfortably in a number of positions. The radius of the cylinder is 24 inches, the bottom flat width is 24 inches, and the length is 77 inches. This arrangement has a habitable volume of 68.8 cubic feet. The The shield mass as can be seen in Table 9 is only slightly greater than the first arrangement. This is considered a near optimum configuration and is illustrated in Figure 13.

The fourth configuration is for a two man arrangement. This configuration is made by splitting the third configuration in half and adding a rectangular section in the middle 41.5 inches high by 24 inches wide. This results in a volume per crewman of 56.6 feet, and provides a habitable volume, which appears even more comfortable than the third configuration.

The fifth configuration is a two man arrangement. If the storm shelter is to be incorporated into some lunar vehicle then the two man side by side arrangement of the fourth configuration may not be feasible, and a vertically stacked arrangement may be necessary. For this configuration a rectangular cross section 82.25 inches high x 24 inches wide with a length of 77" is a lower limit of size and has a volume per crewman of 44 cubic feet. Because of the rectangular arrangement, if the floor width is increased by 1.5 inches the crewman can lie with knees at right angles to the body, a significant increase in comfort. The disadvantages of this arrangement are that the crewmen are isolated, and that their movements are more restricted than in the side by side arrangement.

Thus arrangements for the protection of one or two crewmen in the minimum function chamber varies from 44 to 117.6 cubic feet per crewman. These arrangements probably have an upper limit of occupancy of 10 days.

For larger numbers of crewman the addition of one or two vertical or horizontal arrangements can be use to determine required volume per crewman. As the number of occupants of the shelter increase beyond two the shielding area per crewman will decrease while self shielding by the crew increases. The final optimal configurations will depend upon both the mass of shielding surrounding these volumes and the outside dimensions of the shielded volume.

Low atomic number materials like hydrocarbons have the advantage of minimizing weight requirements by requiring less grams per $cm^2$ and minimizing the production of secondary radiations. These materials, however, have the disadvantage of low density, which requires that the external volume be larger than the higher atomic number material such as aluminum. The optimum shielding weight and volume may be a shield composed of both materials. For these chambers, because they will be at remote sites with limited capability, it is felt that the liquids should not be used because the shield may not be completely filled, temperature problems if cryogenics are used, and the potential for leaks to develop.

In Table 9 there are two cases which establish outside volume and shield mass. In one case the shield may be in lunar orbit and protons arrive from nearly all directions. In this case all areas surrounding the habitable volume are shielded (4 pi shielding). This is conservative, but eliminates any question of the effect of lunar terrain or the mounting of the volume on the lunar terrain. In the second case the volumes are on the lunar surface and for this case the flat areas on which the crewmen rest are not shielded (2 pi shielding).

In Table 9 the dose is calculated at a point at the approximate center of the empty shelter. No allowance has been made for the self-shielding of the body. The body will attenuate the radiation through about 2 pi stereradians from the side opposite to the point in the body where the dose is to be measured. This self shielding varies considerably from point to point on the body. The dose rate to organs at 5 cm depth, the value commonly quoted in the rules and literature for the dose to the blood forming organs, varies from organ to organ when the body is in a fixed position. Further variation will occur in the shelter as the crewman assumes various positions. When a shelter is designed to contain 2 or more crewman, mutual shielding occurs, and considerable variation in dose on the lunar surface between a crewmen in an upper module and a crewman in a lower module will occur.

In Table 9, mass, etc. for the concept of stacking modules to provide shielding for a larger number of men was calculated to show variations in shield mass as volume increases; no mutual shielding was taken into account. These results over-estimate the shielding requirements in the 4 man and up minimum volumes. For the case where the minimum volume is completely surrounded by other volumes, the dose approaches zero, while the maximum dose occurs at an outside corner. The question of whether all the minimum volumes are filled in every case also adds to the uncertainty of a "whole body" dose calculation. The larger number of men volumes have been included to give some preliminary feel of shield mass requirements as shielded volume increases.

Figure 13 shows the arrangement of a single occupant storm shelter. Note that the penetrations for air are located so as to avoid radiation leaks. The shelter is not self-sufficient and all support facilities are supplied by the vehicle. To monitor the vehicle systems and to have some control of vehicle operations, a lap type computer is provided together with communications equipment to communicate with the main base. A view port allows some visual inspection in the immediate vicinity of the shelter. An access port is provided so that food and water can be stored exterior to the protected volume, and waste products removed from the volume. Waste handling facilities are similar to those used in the Gemini program so that installed facilities are not required.

## 6.3 STORM SHELTER AND MAXIMUM FUNCTION CHAMBERS

Two approaches are considered for these chambers:

1) A storm shelter approach for a short duration mission of 30 days or less, which limits dose to the emergency limit of 20 REM.

2) A large chamber for missions in excess of 30 days. This chamber is capable of supporting all IVA operations. The dose rate at all times within this chamber is equivalent to the background level encountered on Earth due to galactic cosmic rays.

### 6.3.1 STORM SHELTER

The storm shelter is conceived as able to support 4 men for a period of up to 10 days. A conceptual design of the interior is shown in Figure 14. Two methods of providing shielding are proposed:

1) An Earth fabricated shielded chamber transported from Earth. The mass of such a chamber is estimated at 14.7 m tons (63.6 gm/cm$^2$ for aluminum) and has an interior volume of 265 cubic feet. 4 pi shielding is assumed. The same shelter with 2 pi shielding, sitting flat on the surface, would weigh 11.5 m tons. Because this shelter will be close to a landing and take off site, it is subject to bombardment from ejecta generated by transport vehicle engine exhaust. For this reason the shield is made of aluminum to insure good impact resistance. Other materials will not change the mass of the shelter significantly.

2) The alternate to this heavily shielded structure is a thin shell estimated at 3/16" wall thickness. This chamber is estimated to weigh 5 to 6 hundred lbs. (~300 kgms) and has an external volume of approximately 270 ft$^3$. Actual construction would be similar to aircraft fuselage construction with stiffeners and a very thin skin. Lunar soil is used for shielding. The soil thickness need only be sufficient to limit the dose to 20 REM. To provide the required 63.6 gm/cm$^2$ thickness, assuming a density of 1 gm/cm$^3$, requires 2.18 feet of lunar soil. Between 880 and 950 ft$^3$ of soil, depending on burial depth, must be moved. If available, a backhoe blade attached to the lunar rover or a small teleoperated earth mover are required to bury the module. Around 3,000 hand shovel loads would be required to move this amount of material if 1/3 ft$^3$ per load is assumed.

   An airlock is required for transfer to this shelter, and the tunnel connecting the airlock to the chamber must have direction changes to not produce a shielding penetration, which would allow a high dose rate in the interior of the shelter. As was the case for the minimum function chamber, air, electricity, and computer interface are incorporated into the chamber. There is sufficient space to provide food storage and waste disposal within the chamber. With some additional amenities, the soil covered storm shelter could find use as a "line-shack" for semi-permanently manned remote sites. A study of ways and means of modularizing this storm shelter so that a series of these chambers can be connected to provide the maximum function chamber described in the next section of this report should be an integral part of the detailed design of the storm shelter.

### 6.3.2 MAXIMUM FUNCTION CHAMBERS

These chambers are of sufficient volume to allow the performance of all IVA operations over extended periods from 6 months to three or more years. They consist of a habitation area and a working area. These chambers protect against the continuous exposure to galactic cosmic rays, and as a result also completely protect from solar proton events, since the shielding requirement for the galactic cosmic rays far exceeds the requirement for solar proton events.

Table 10 lists the volumes of several spacecraft, the volume per man and the volume per man day. From this data it is estimated that between 4 to 7.67ft$^3$/man day is the range of volumes per man day applicable to a lunar base. A typical lunar base, supporting 4 crewmen would require a volume of between 2,880 and 5,522 ft$^3$. For shielding estimates, a volume of 4,000 cubic feet is selected.

If these structures are covered with lunar soil (silica) to a shielding thickness equivalent to 750 gm/cm$^2$ of air, 778 gm/cm$^2$ of silica will be required (assuming that the range relationship of equation 9 is adequate for estimating the shielding attenuation process). This thickness corresponds to an altitude of about 9,000 ft in the atmosphere, and is about the upper limit of elevation where people regularly live. This will serve as a guide to the amount of lunar soil required to shield the lunar base. Further refinement of this number should be made using the computer programs of reference 1 and the exact composition of the lunar soil. The lunar soil should be checked for radioactive material.

Assuming a density of 1.5 gm/cm$^3$ for the lunar soil (estimated density with poor packing), an angle of repose of 30 degrees, and a shield thickness of 17 feet, if the volume is represented by a box 77 inches high and a square floor plan 24.97 feet on a side, which is buried 3.28 feet into the lunar surface (1 meter is the estimated thickness of loose soil on the lunar surface), then 66,106 cubic feet or (3,094 tons) must moved to create a shield. Other papers on buried lunar structures have estimated shielding thickness as about 3 meters or about 9.8 feet. An assumption of higher density (~ 2.6), which is within the range of the density of lunar material, would yield a 3 meter thickness for the shield described here in units of gm/cm$^2$ (~ 785 gm/cm$^2$). A low density assumption of 1 gm/cm$^3$ would lead to a shield 7.8 meters thick.

Two alternates to this approach are possible:

1) Transport shielding material from Earth or;

2) Allow a higher dose during IVA operations from galactic cosmic rays, thus increasing the shielding thickness for solar proton events during EVA operations.

Transporting the materials from Earth and using no burial on the lunar surface, but not shielding the bottom gives the following results:

| Material | Shield Thickness Ft | Volume Ft3 | Mass tons |
|---|---|---|---|
| Carbon Composite | 15.86 | 67,574 | 3,162 |
| Aluminum | 10.40 | 31,219 | 2,630 |
| Water* | 21.44 | 124,215 | 4,263 |

*10% allowance made for containment

Note that the amount of material to be handled on the lunar surface after delivery from Earth is about the same as the mass moved in excavation. There appears to be no reason to consider delivering material from Earth.

## Table 10
## Manned Spacecraft Mass Habitable Volumes and Crew Times

| Spacecraft | Mass | Crew | Stay Time (days) | Habitable Volume(ft$^3$) | Volume ft$^3$/Man | Volume ft$^3$/Man day |
|---|---|---|---|---|---|---|
| Mercury | 2,400(at recovery) | 1 | <1 | 55 | 5> | 55 |
| Gemini | 5,900(with Heatshield) | 2 | 14 | 80 | 40 | 2.86 |
| Apollo LEM Ascent | 4,000 (w/o Engine) | 2 | 8 | 159 | 79.5 | 9.93 |
| Apollo Command Module | 6,400 (w/o Heatshield) | 3 | 14 | 208 | 69.3 | 4.95 |
| Soyuz | 13,500 (total) | 3 | 30 (? crew) | 363 | 121<br>(assume crew of 3) | 4.00 |
| Salyut | 41,675 | 3 | 237 (2 crew) | 3,500 | 1166 | 7.38 |
| Mir | 44,000 | 6 | 300+(2 men) | 4,600 | 766 | 7.67 |
| Space Shuttle | 190,000 | 7 | 30 (? crew) | 2,625 | 375 | 12.5 |
| Skylab | 203,000 | 3 | 84 | 12,800 | 4267 | 50.7 |
| Mir Complex | 235,000 | 6 | ? | 18,000 | 3000 | 16.7 (assume 180days) |
| Space Station | 278,000 | 8 | 180-250? | 8,000 | 1000 | 5.5 (180 days)<br>4 (250 days) |

The creation of shielding from lunar material has been considered by a number of authors. This study closely parallels those in reference 15. In reference 15 two additional concepts for covering the chamber were discussed. The chamber in that design was a cylinder 4.45 meters in diameter with a length of 7.23 meters, hence the volume is about the same as that given above. Retaining bulkheads to eliminate the sloped sides were proposed. This will entail shipping the retaining bulkheads from Earth. The amount of reduction in the amount of soil is not stated. The principal advantage of this system is that a conveyor belt is used to transport material to the top of the shelter, which should reduce the time required to cover the structure. Excavation is carried out with a bulldozer. Unless the conveyor belt is used for other lunar applications in mining it is not clear that the transportation cost in delivering it from Earth together with the cost of the bulkhead transportation provide an overall saving in the erection of the lunar shelter. The principal disadvantage of the bulkhead system is that it assumes a predetermined mass per unit area, and no adjustment appears possible if the material retained within the bulkhead system does not achieve the required gms/cm$^2$.

The second method proposed was the use of sand bags. Again the reduction in the mass of shielding is not stated. The method of loading the sand bags and their placement on the shelter was not described, so the overall saving in placing the shielding could not be determined. These two concepts are shown in Figures 15 and 16. The sand bag arrangement has the disadvantage that voids are created in the shield between sand bags, and these voids can be a source of local radiation hot spots.

In reference 16 a number of concepts for an inflatable structure for use in a lunar shelter were advanced. The spherical structure, shown in Figure 17 was one of the leading candidates. For site preparation, blasting a hole to bury part of the sphere was considered. Unless the hole is created prior to landing, the ejecta from the blast (based upon the data presented in reference 17) may require that the landing site and the blast site be separated by about 2.5 kilometers. Sand bag covering was the proposed method of providing shielding.

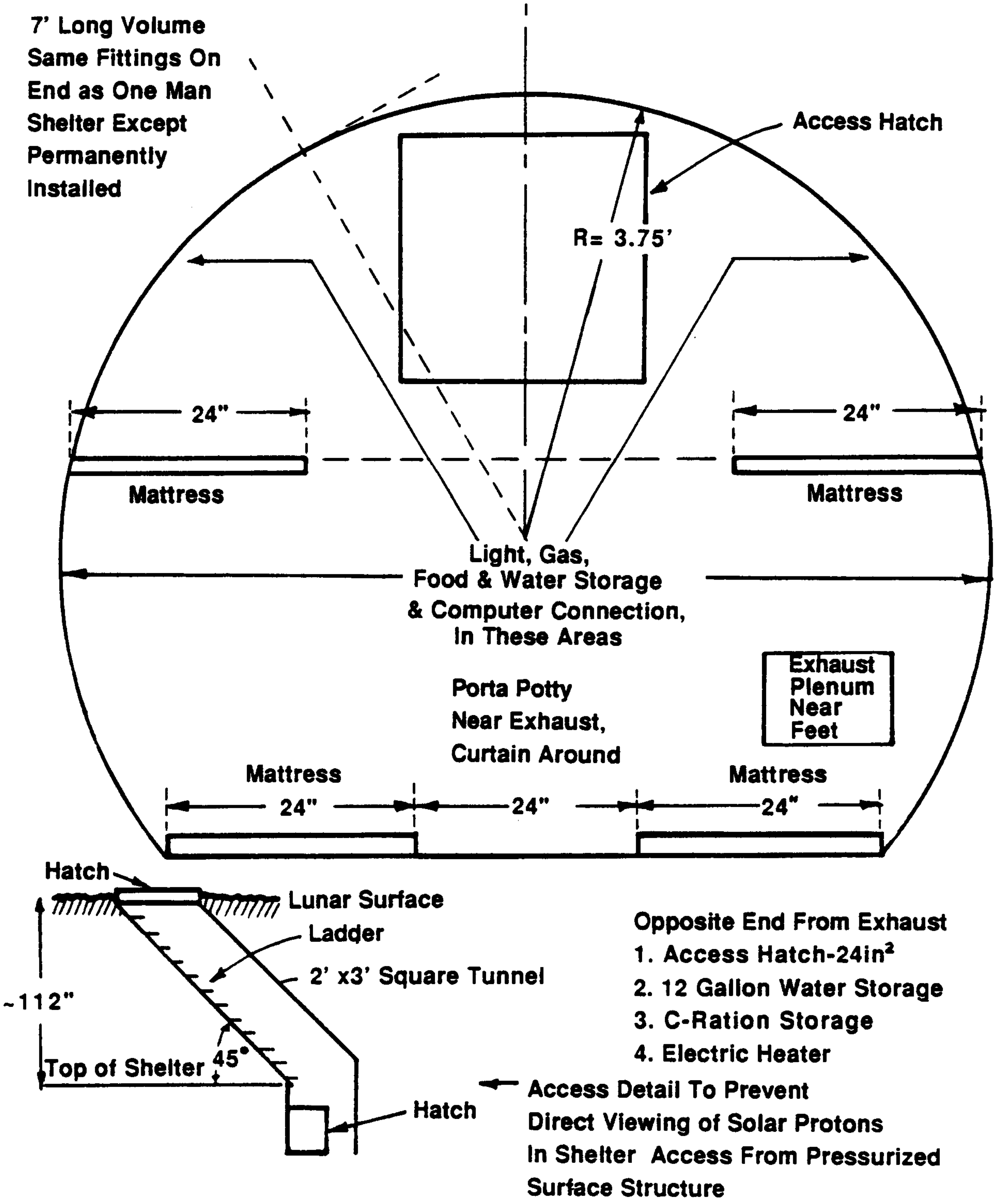
None of the studies have calculated the energy required to move the soil needed for shielding. However, it would appear that the movement of soil in the vertical direction should be kept to a minimum. This would indicate that the lunar shelter should be made with a minimum height. The energy costs of moving regolith vertically and horizontally need to be determined.

## 6.4 NO SHIELDING CONSIDERATIONS

If none of the above shelter configurations are found operationally feasible very early in the exploration program, then the mission should be planned for periods when the sun is quiet. As can be seen in Figure 2 only very small flares, which have little or no impact on dose, have occurred during the period when the sunspot number was below around 35. The sunspot number may be below this value for 4 or more years while one cycle is ending and another is starting. The probability of encountering a major solar flare may be considered low enough to be ignored.

Figure 14

# 4 Man Buried Storm Shelter



Opposite End From Exhaust
1. Access Hatch-24in²
2. 12 Gallon Water Storage
3. C-Ration Storage
4. Electric Heater

Access Detail To Prevent Direct Viewing of Solar Protons In Shelter Access From Pressurized Surface Structure

Figure 15, Lunar Shelter with Bulkheads

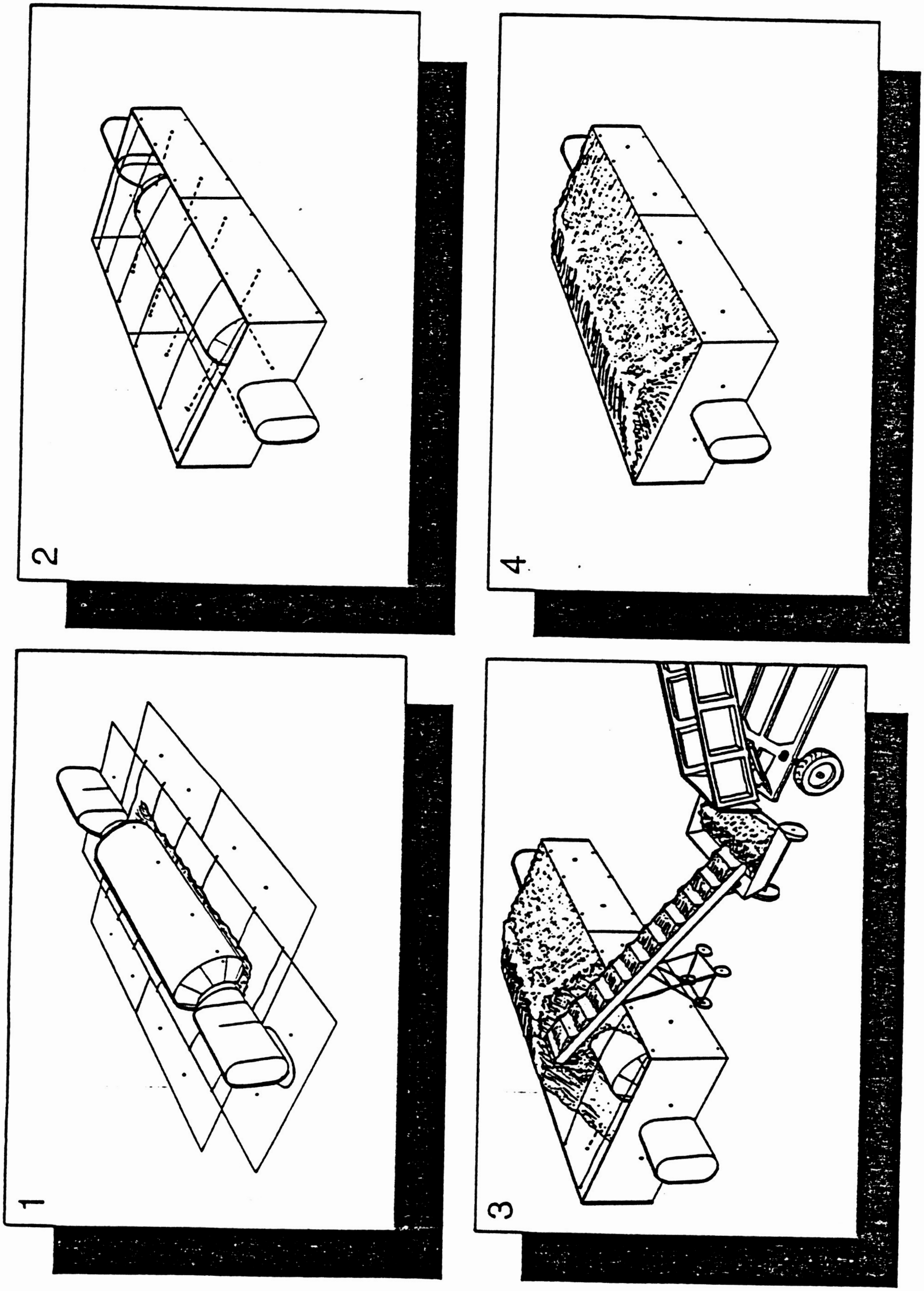


Figure 16, Lunar Shelter Buried and Sandbags

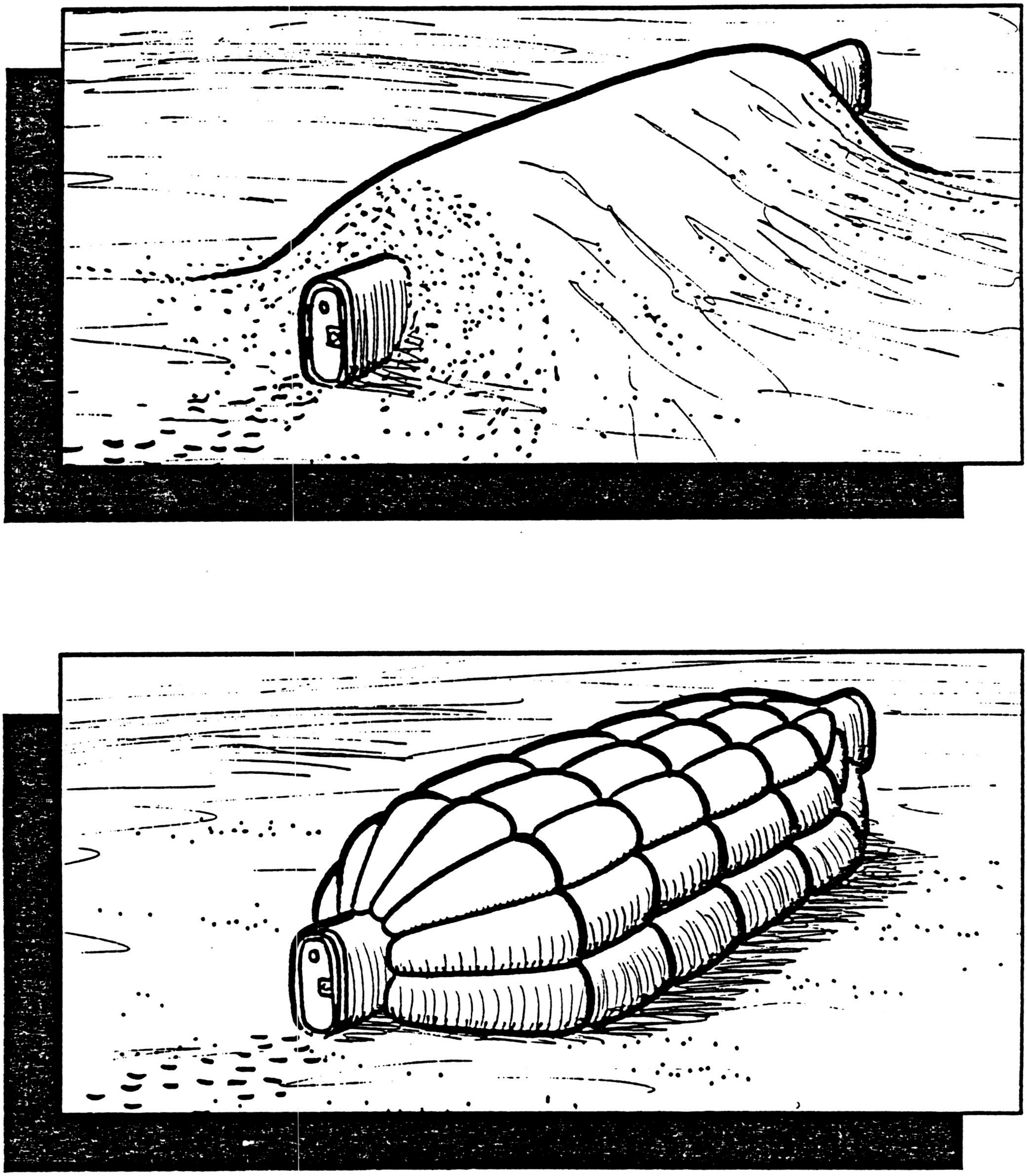
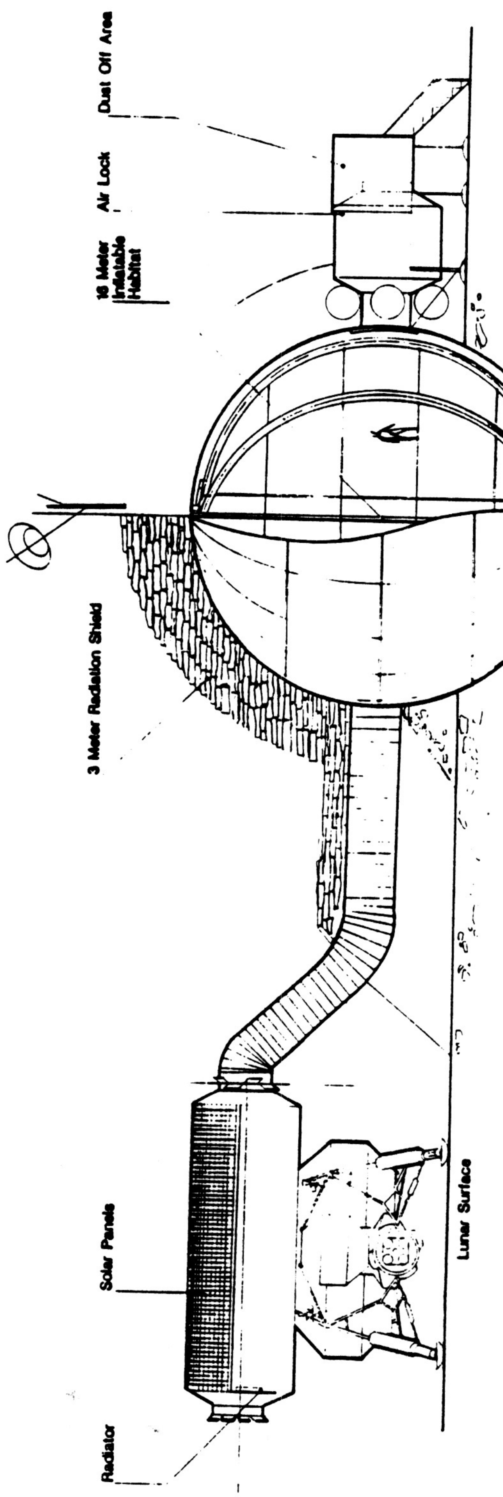


Figure 17, Proposed Inflatable Structure from Reference 16



# 7.0 RADIATION MEASUREMENTS

## 7.1 VEHICLE PROBING WITH GAMMA RAYS TO DETERMINE MASS DISTRIBUTION

Radiation is used to determine the shielding thickness at various solid angle directions in a spacecraft, and thus provides quantitative data on which shielding effects of solar particle radiation can be evaluated. In references 18 through 20 the details of using a gamma ray source close to the surface of the Apollo and Gemini spacecraft are described. Using this data the precise dose calculations could be carried out for various points in these spacecraft. This technique can provide the most precise estimate of the dose received in the various transport vehicles being considered for lunar exploration, and may influence the arrangement of equipment in the vehicle to minimize radiation exposure.

## 7.2 RADIATION PROTECTION MONITORING EQUIPMENT

### 7.2.1 SHIELDING INTEGRITY SURVEY

Because there will be considerable uncertainty about the packing density of lunar soil, one of the early checks of the maximum chamber will be to insure that adequate shielding has been placed around the structure to establish that conditions closely match those found in an equivalent Earth situation. Geiger counters or scintillation counters are the simplest and most reliable meters for this application. To insure that cosmic rays and not background contamination are measured, coincidence counting using two counters separated by a few inches may be used. In addition to the determination that the shield is of adequate thickness, surveys should be conducted to determine that penetrations, such as access hatches, do not produce local hot spots. In the case of loose lunar soil being used as the shield, regular checks should be conducted to insure that there has been no change in the shielding due to local operations. These instruments should be calibrated on Earth at an altitude that corresponds to the proposed shield thickness on the permanent lunar habitat. The count rate of galactic cosmic rays may be adequate for testing the storm shelter configuration during solar minimum, but because the intensity changes slowly with thickness at solar maximum, an alternate radiation source or some other method of determining the soil thickness will be required.

### 7.2.2 PERSONNEL MONITORING DEVICES

Personnel monitoring requires two types of instruments rate meters and dosimeters:

#### 7.2.2.1 RATE METERS

A rate meter device which performs two functions, an alarm warning of the start of a solar event and an indication that the dose rate has dropped to a level low enough to resume normal operations. For this application a tissue equivalent ion chamber or proportional counter should be used. Lithium drift silicon detectors may be calibrated so as to be used in this application.

The instrument will probably have two detectors. The first would have a light shield corresponding to the thickness of the material making up the spacesuit. The second detector would have an additional 5 cm of shielding. The first detector is an indicator of skin dose; while the second indicates the depth dose at the blood forming organs. The electronics associated with this instrument should have a response over a range of 4 decades, which is the range of dose from background to the peak intensity observed on the largest solar proton event. Data storage similar to that used in hand held computers could be enabled when an alarm level is reached. This storage would perform two functions. It would record the intensity at fixed time intervals and would integrate the dose over the entire period of exposure from both meters. The meter should be cable connected to the on-board computer. It can then be left in the open to record radiation levels, but is able to transmit this information to crewmen in a shelter and to transmit the information to the main lunar base.

Meters of this type read the dose in RAD. At present there are no instruments which directly read the dose in REM. A proposed design of a REM instrument was described in reference 21, but was never constructed. This instrument proposed to use an arrangement of coincidence counters to establish energy levels, and by weighing the outputs establish the REM dose.

Some digression is needed here to describe the method of establishing RBE. The RBE is related to the density of ionization along the path of a particle or ray as it passes through a material. To gamma or X-rays all materials appear semi-transparent. They impart their energy sparsely as they pass through the material. Charged particles, on the other hand, produce a dense trail of continuous ionization. The ionization per unit length of path of an ionizing particle is defined as linear energy transfer (LET). The greater the charge, the greater the ionization, and the slower the particle, the denser the ionization. Along these paths, the denser the ionization, the more damage to living tissue is considered lethal.

Ion chambers collect only the electrons produced by the radiation source. Several ionization events from several particles may be occurring simultaneously. The ion chamber records the ionization produced by these particles but makes no discrimination as to the "quality" or ion density of the tracks in which the radiation is produced. A REM meter must be able to make this discrimination. Dr. J. A. Angelo of EG&G told the author that EG&G is in the process of designing such a meter.

Since the REM is by definition a measure of biological response there is still some controversy as to what weighing or RBE value should be applied to LET values measured in a detector. The RBE for thermal neutrons is 10, and this level was established on the basis of cataract formation in the eyes. The response of the blood forming organs to this type radiation may be different. In the future it would be helpful if the definition of RBE was for a specific organ or a specific response.

In the past, nuclear emulsions in which ionization along a track could be measured have been used to convert RAD dose to REM dose, but no realtime measurement has been made. This device should have equal response over all directions. This instrument is bulky and is unsuitable for performing surveys in a vehicle to determine high radiation sites if they exist. A second meter with a smaller detector, but lacking good omnidirectional properties, should be available for conducting such surveys.

### 7.2.2.2 DOSIMETRY DEVICES

Dosimeter devices are designed to measure the radiation dose received by an individual. There are two types: those that can be read in the field and those which are processed in the laboratory.

#### 7.2.2.2.1 DEVICES READ IN THE FIELD

The type that can be read in the field are a miniature version of the rate meter described above, except that only a smaller single chamber is used. These devices are battery powered and can read up to a total of 1,000 RAD and are accurate up to dose rates of 100 RAD/hr. Battery life should be about 2,000 hours.

#### 7.2.2.2.2 DEVICES READ IN THE LABORATORY

There are a number of devices which cannot be read in the field. Lithium fluoride when exposed to radiation, and subsequently heated, emits light. The amount of light is proportional to the dose received by the material. In the laboratory a weighed amount of the exposed material is heated to 240°C in 30 seconds on a small planchet in an enclosed space. A photomultiplier tube measures the amount of light emitted. Fifty mg is the usual amount used to perform this measurement. For exposure in the field samples of this size or larger are sealed in polyethylene tubing. A typical tubing is about 1 to 2 inches long and about 1/8 inch in diameter. As was pointed out in the section on shielding, the dose received at various points in the body vary widely. Dosimeters of this type, since they require little mass or volume, can be used to measure several points in the body to determine dose distribution. In laboratory studies of dose distribution in a plastic or water filled model (phantom), animal, or cadaver the dose at any point in the body can be determined.

Photographic film shows a logarithmic response to ionizing radiation. Two methods of evaluation are used. First the overall greying of the film can be observed with a densitometer. For this method to be successful rigid control of temperature and developing time must be used. Small packets using wrappings similar to that use for dental film are used. Small shields are placed around the dosimeter to establish the types of radiation to which the film was exposed.

The second use of photographic material is to create an emulsion which can then be packaged in a bar about 1 inch square and a few inches long. In the laboratory the bar is separated into thin layers and developed. The finished strips are then examined under a microscope to examine the individual tracks made by the various radiations. This allows the determination of the energy of the particles and from an analysis of LET values, the RBE can be estimated.

There are no biological measurements which are at present correlated to the physical dose measurements at low and intermediate doses. Background information on blood changes should be collected, and, in the event of a large emergency dose, changes in blood measurements will provide some guidance in determining if acute radiation symptoms are likely to develop.

### 7.3 SPECTROMETERS

Spectrometers are used to determine the differential energy spectrum of particles. From an operations standpoint this information is of value in verifying shield design, and the information is also of use to scientists studying space particle events. These instruments would indicate any difference in the intensities of particles arriving at the Moon compared to data collected on Earth or by satellites.

## 8.0 FLARE PREDICTION STATUS

A brief description of solar flare phenomena will provide the background of what might be attained by prediction of solar flares.

The oldest continuous data on solar activity are sunspots. Data exists starting in 1755. A sunspot observed near the center of the sun's disk shows a dark central region called the umbra surrounded by a grey region called the penumbra. The umbra can be as large as 75,000 km in a very large spot. The sun rotates about its axis with a average period of 27 days. The period is not a constant, but varies with latitude. Sun spots show a typical 11 year cycle, which may vary by about a year from cycle to cycle. The activity varies from cycle to cycle, and predictions based on previous cycles have failed to agree with previous events. An 80 year cycle appears to be superimposed on the 11 year cycle, and the last maximum in this cycle appeared to be reached in cycle 19 in 1958. The rotation of the sun imposes a 27 day cycle on the preceding cycles. Nearly all the sun spots are confined to a region of from 5° to 30° above and below the equator. The first spots of a new cycle appear in the high latitude region, while some spots of the old cycle are still in the region near the equator. At sun spot maximum most of the sunspots are concentrated around 15° latitude. The phenomena associated with the onset of a solar flare are:

An increase in brightness in the visible region
An increase in light emission in the hydrogen Lyman alpha region
Bursts of radio noise in the 1000 Mc and 200 Mc regions
Burst of X-ray noise

The arrival of protons at Earth produce a number of interactions with the Earth's atmosphere: aurora, absorption of galactic radio noise, and interruption of long range radio communication. These phenomena are associated with ionization of the upper atmosphere. If the flare contains very high energy particles (relativistic energies) then instruments can detect the presence of neutrons generated by the solar protons at ground level.

The condition of the magnetic field in the region between the Earth and the sun influences the ability of the solar particles to reach the Earth. Solar particles are confined to a bottle-like region, which is determined by the strength and direction of this magnetic field.

Forecasting relies on the observation of all these phenomena. Long range forecasting, on the order of months, relies upon the sun spot number. Intermediate forecasts, in days, rely upon the size and location of the sun spots on the solar disk and the complexity of the sun spot groupings. The condition of the magnetic field may make it difficult for particles to reach the Earth or the fields may steer the particles away from the Earth. The observation of the variation in intensity with time of the electromagnetic phenomena, which precede the arrival of particles at the Earth by about one or two hours, are used to estimate the magnitude of the flare. A review of the papers presented at the Solar-Terrestrial Predictions Proceeding at Meudon, France in 1984 indicates that the forecasting is being actively pursued; however, forecasting the magnitude of an event greater than some value has false alarm rates approaching 50 percent.

In summary, at the present state of the art, it appears the observations in the visible, X-ray and radio frequency can provide a warning an hour or two before the arrival of solar particles. A forecast of a large event, however, may give a false report half the time.

## 9.0 MAGNETIC SHIELDING

A particle moving at a constant velocity at right angles to a uniform magnetic field moves in a circle. The diameter of this circle is:

$$D = 2mv/qB \tag{17}$$

Where:

m is the mass of the particle
v is velocity
q is the particle charge
B is the magnetic field strength

A particle entering such a field has its direction reversed in a distance D/2. Uniform fields of this type are achievable only between the poles of a magnet. For spacecraft applications the field of a torus must be used. In this case the magnetic field varies with the cosine of the angle to the plane of the torus and is inversely proportional to the cube of the distance from the torus. This is the type of field that is present around the Earth. Charged particles in such a field follow a complex path that has been described by Stormer. For more information the reader should consult any good text on geomagnetism. Stormer's work showed that within a certain solid angle, particles of a certain energy are excluded from reaching the Earth. This type of motion is applied to a spacecraft to exclude certain particles from reaching the shielded volume of the spacecraft. The magnetic field must be high to exclude the particles. The effects of high magnetic fields on humans are not desirable. Therefore the field must be arranged to provide a habitable volume where the magnetic field approaches zero.

In reference 23 two arrangements of coils to achieve these two requirements have been shown and are shown in Figure 18. The magnetic field cuts off particles below a certain energy, but the particles that do penetrate the magnetic field are not degraded in energy. The cut-off energy is determined by the strength of the field, which is determined by the electrical current flowing in the coils of the torus. To protect against those particles which penetrate the magnetic fields, mass shielding is required. Thus electromagnetic shielding is a hybrid system relying both on electrical current and mass shielding. In reference 23 the current density required to produce the field was estimated at $10^9$ amperes/meter$^2$, which is much higher than present practice. This current density provides a cut off energy of 150 Mev.

The current places the structure supporting the inner coil in compression and the outer coil support structure in tension. The pressure between the coils is proportional to the current and the length of the conductor. The mass of the structure is determined by both the mass shielding and the stresses imposed by the current. To maintain the current level with a minimum expenditure of power, superconductor coils must be used. When reference 23 was written superconductors operated in a temperature range near absolute zero and liquid helium circulating around the coils was required to maintain superconductivity. The recent developments in super conductivity may allow liquid oxygen or nitrogen to be used. The radiant heat load from the sun determines the amount of cooling required to maintain the superconductor at temperature. Both insulation and refrigeration are used to minimize the amount of energy required to maintain the required temperature. The system may be operated open loop (allowing the spent refrigerant to escape to space) or closed loop with a refrigeration cycle. The refrigeration-insulation system of Reference 23 made up about 1/3 of the total weight of the magnetic shielding system. To produce the same dose in the spacecraft, the overall system weight was 71 percent of the weight of a conventional shield.

The system design described above was conceptual, and a number of factors must be determined before feasibility can be demonstrated:

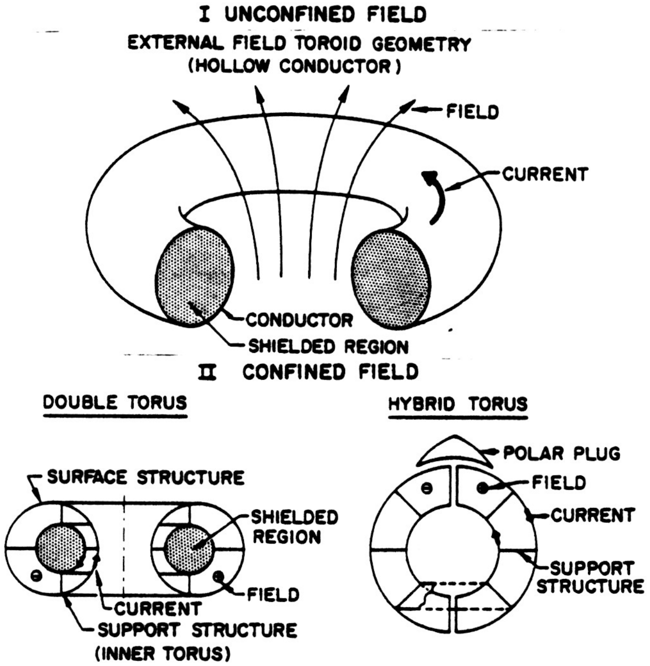
1) It appears that only single particles were considered in reference 23, but in reference 24 it was demonstrated that when a large flux of particles entered the Earth's magnetic field, lower energy particles could reach the Earth. Thus the degree of protection provided by a magnetic shield may be lower than that shown in reference 23. Hence a successful design should require higher current densities than those shown in reference 23, which are above the current state of the art.

2) The new higher temperature superconductors are ceramics and their physical properties need description.

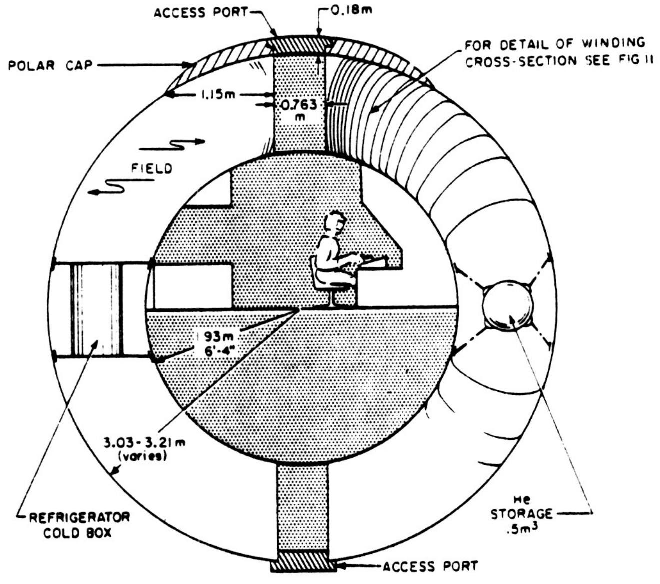
3) The energy stored in the magnetic field is in thousands of foot pounds. Interruption of the current flow will impose a substantial shock load to the structure. The energy stored is proportional to the product of the current squared and the coil length.

4) The magnetic shield will require a continuous input of power or the expenditure of consumables to maintain the superconductor at temperature.

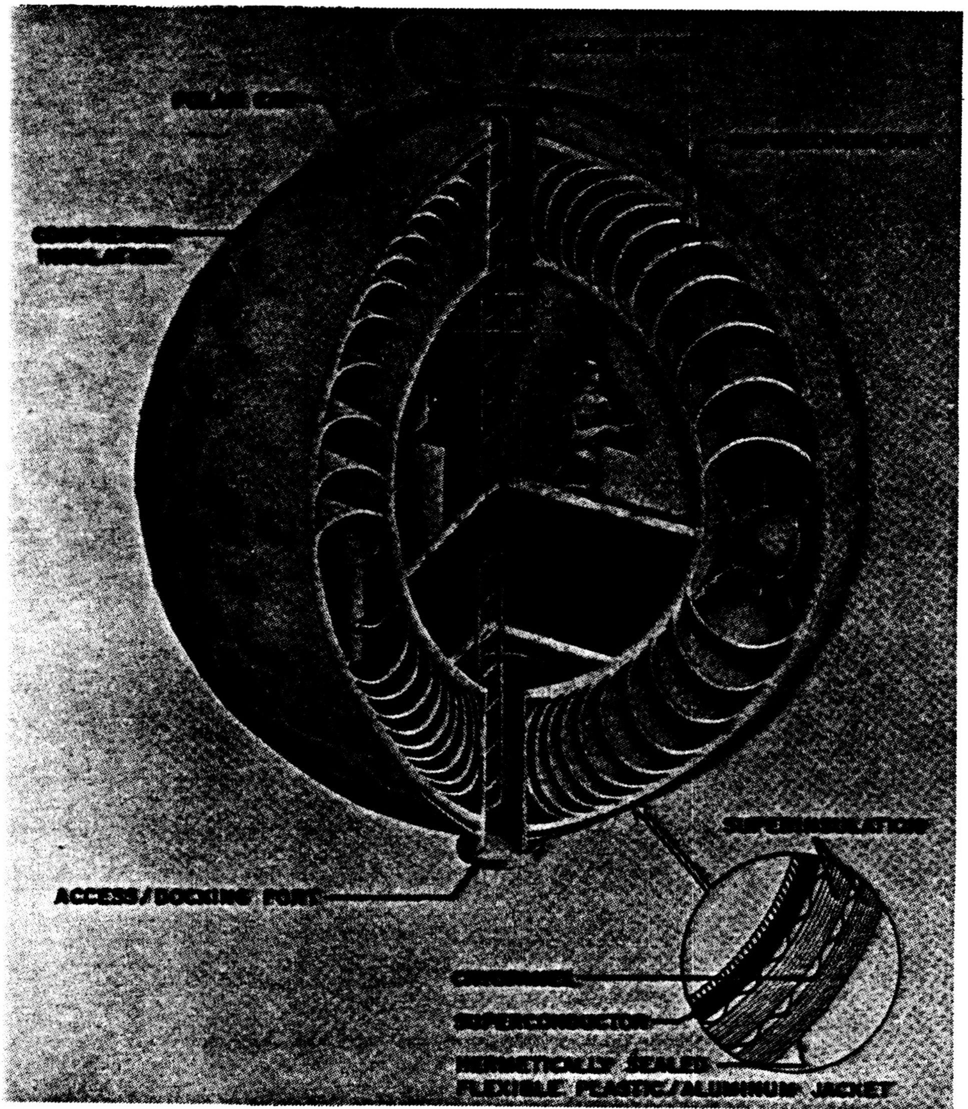
Figure 18, Field Coil Arrangements for Electromagnetic Shielding (Ref. 23)



Magnetic Field Configuration



Detail of winding cross-section, hybrid magnetic field



Cross-section of superconducting magnetic hybrid geometry solar flare shelter, shielded volume; 30 m3, equivalent shielding level: 25 g/cm3

## 10.0 CONCLUSIONS

In this paper the requirements for a radiation protection program for the exploration and permanent occupancy of the lunar surface have been described. The following conclusions are drawn.

### 10.1 EARLY MISSIONS OF SHORT DURATION (~8 DAYS)

For these missions there is no lunar infrastructure support. The radiation risks in these missions are essentially the same as those encountered in the Apollo Program. If possible, these missions should be performed during periods of low solar activity. Radiation protective measures would be limited to instrumentation and possibly partial protective garments.

### 10.2 INTERMEDIATE MISSIONS OF DURATIONS UP TO 2 MONTHS OR EXPLORATORY MISSIONS OF SIMILAR DURATION AFTER INSTALLATION OF A PERMANENT LUNAR BASE

Missions of this length will be used to develop the permanent lunar infrastructure, will be exploration missions over the lunar surface, and will support the manning of remote sites for various scientific missions. For these operations the total mission dose of radiation for periods of solar calm is limited to 5 REM irrespective of lunar stay time. Radiation monitoring equipment must be supplied for these missions. An emergency dose of 20 REM is the maximum allowed in the event of a large solar flare. To provide this level of protection a Buried 4 Man Storm Shelter at the site of the permanent lunar base, using lunar soil as the shielding medium, is recommended; and shelters of this type are recommended for semipermanent remote sites. The incorporation of shielding into vehicles which are used in nomadic type exploration would appear to seriously degrade the performance of such vehicles. Evacuation of personnel to a storm shelter or to the permanent lunar base is the preferred option for this case. Ideally this evacuation should be performed before the peak intensity of the solar event is encountered. Warning for such an evacuation is 3 hours or less. The use of a partial protection garment may extend the rescue period when a permanent lunar base with an interior dose equal to Earth background is in place, but in no case should the emergency dose exceed 20 REM.

## 10.3 PERMANENT BASE OPERATIONS

For stay times of 180 or more days a permanent shelter with sufficient shielding to reduce the dose to Earth background level (750 gms/cm$^2$ or 3 to 8 meters of lunar soil depending on the density) is used to protect the occupants. For EVA and remote base operations, the dose for solar quiet conditions (i.e. galactic cosmic ray dose), is limited to 5 REM over the duration of a crew stay. Crew rotation and possibly teleoperations will be required to keep the non-emergency dose to this limit.

## 11.0 RECOMMENDATIONS

The following recommendations resulted from this study:

1. Dose Limits. Acute radiation effects cannot be ignored. The evidence to support this position is limited, and experimental research to cover the dose range between 0 to 50 REM in a short period of time as it relates to operational performance of a crew is needed. If possible, a biological response, which can be measured (blood changes appear the best candidates) is highly desirable to establish individual susceptibility to acute radiation effects, rather than the carcinogenic long range effects, which are statistical.

2. Partial Protection Garment. The interfacing of a partial protection garment with a spacesuit to optimize the tradeoffs under operational conditions between mobility and protection should be undertaken. The NASA Weightless Environment Training Facility appears ideal for this type of study.

3. Storm Shelters. The buried type storm cellar appears the best approach for "lineshack" type operations at semi-permanent remote sites. An inflatable or collapsible structure which can be buried is needed to minimize weight which must be transported to such sites. Incorporating a backhoe into lunar surface designs may allow a similar type structure to be used on long duration nomadic surface vehicles, and thus reduce the requirement for evacuations to the permanent lunar base. The method of providing logistic support such as power, atmosphere, communications, and other systems, needs more detailed investigation.

4. Permanent Lunar Base. A design which is modular so expansion as the permanent base grows should be considered. This type of design will be easier to shield early in the program, because the initial habitats will be smaller.

5. Teleoperations. Operations of this type should be part of a long range plan which reduces EVA time and hence radiation risks.

6. REM meter. The development of electronic radiation instruments with a REM response based on anticipated acute effects is recommended.

7. Shielding & Dose Studies. For future studies it is recommended that a standard solar proton event be defined, in which intensity as a function of time is defined.

8. The galactic cosmic ray environment should be fixed at some period in the solar cycle or the variation with solar activity defined.

9. Shielding programs should be specified as well as the input parameters for various materials to be employed in shielding.

10. A shielding manual, specification, or data base, which incorporates the standards derived from items 7 through 9 above is needed.

# APPENDIX A

## ESTIMATION OF REQUIRED SHIELD THICKNESS FOR MODEL EVENT

I. Allowed dose per unit flux greater than 30 Mev

| | |
|---|---|
| Model flare size | $1\mathrm{x}10^{10}$(p>30Mev) |
| Lunar surface flux (2Pi geometry) | $5\mathrm{x}10^{9}$ (p>30Mev) |
| Allowed dose | 20 REM |
| Ratio REM/RAD (estimated) | 1.7* |
| Allowed RAD dose | 12 RAD |
| RAD dose per lunar surface flux | $2.4\mathrm{x}10^{9}$ |

*Based on ratios of monoenergetic protons from reference 25

II. From reference 11 curve fit data for total dose in RADS (includes secondaries) versus thickness for flares:

$$N(>P) = 4.54\mathrm{x}10^{10}\exp(-P/P') \qquad (p(>P)/cm^2)$$

Input data:

$\mathrm{Flux}=2.2888\mathrm{x}10^{9}$ $\qquad (p(>30Mev)/cm^2)$

| Shield thickness, T, (gm/cm$^2$) | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
|---|---|---|---|---|---|---|---|
| Dose (RADS) | 38 | 9 | 3.3 | 1.6 | 0.72 | 0.40 | 0.22 |

Output equation form:

$$\log[\mathrm{dose(RAD)/Flux}]= A_1+A_2T+A^3{}_T2+A^4T3+A5T^4$$

The output from the above equation yields the following results:

The dose versus thickness is curve fit identical to the above data from 10 gm/cm$^2$ to 50 gm/cm$^2$ . Results are low for values greater than 50 gm/cm$^2$.

The coefficients (Ai) are, in ascending order:

$-6.981\mathrm{x}10^{0},-8.58\mathrm{x}10^{-2},3.91\mathrm{x}10^{-4},2.40\mathrm{x}10^{-5},-3.55\mathrm{x}10^{-7}$

## APPENDIX A
(Continued)

For a cylinder with end caps, the percent of solid angle subtended at its center by the cylindrical portion is 64.2 percent and the balance of the 4 pi solid angle is from the end caps. These solid angle break downs are used to calculate the slant thicknesses through 4 sections of cylinder and two sections of end cap. The required thickness to produce the allowed dose in RADS is obtained by iteration of the spread sheet form which follows:

CYLINDER SECTION

| | Thickness | Log Dose | Dose Rad/Unit Flux |
|---|---|---|---|
| THICKNESS 63.597 | 63.597 | - 8.34304 | 4.539 x $1^{0}\text{-}^{9}$ |
| SLANT THICKNESS (1) | 68.43037 | - 8.59571 | 2.537 x $10^{-9}$ |
| SLANT THICKNESS (2) | 78.72037 | - 9.35295 | 4.44 x $10^{-10}$ |
| SLANT THICKNESS (3) | 100.0890 | -12.2492 | 5.63 x $10^{-13}$ |
| DOSE THRU CYLINDER (4pi) | | | 1.880 x $10^{-9}$ |
| END SECTION | | | |
| THICKNESS GM/CM$^2$ | 63.597 | -8.34304 | 4.539 x $10^{-9}$ |
| SLANT THICKNESS (1) | 69.70231 | -8.67209 | 2.128 x $10^{-9}$ |
| DOSE THRU END (4 pi) | | | 3.333 x $10^{-9}$ |
| WEIGHTED BY SOLID ANGLE SUBTENDED | | | 2.400 x $10^{-9}$ |

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5 GM/CM2 FOR DEPTH TO BLOOD FORMING ORGANS

SHIELD THICKNESS = 63.597-5= 58.597

Note 2 pi geometry accounted for by flux level

## APPENDIX B

## CURVE FITTING OF COEFFICIENTS FOR RANGE AND STOPPING POWER MATERIALS WITH ATOMIC NUMBER UP TO 29

The range and stopping power of a charged particle in passing through a material vary with the number of electrons encountered per gram/cm$^2$, and thus are proportional to the atomic number, Z, of a material. The energy loss in producing ionization is higher in low atomic number materials because the electrons are more closely bound. Accurate values of range and stopping power are required for shielding calculations. For the case where secondary particles do not contribute a large fraction of the energy deposited by the particle, the range or stopping power ratio between different materials can be used to determine the different thicknesses of various materials in a shield using a single shielding material. In reference 11 the parameters for determining the range and stopping power were described for a limited number of materials. The equation describing range is:

$$R(E)=(a/2b)\ln(1+2bE^r) \qquad \text{(A1)}$$

The values a and b are functions of the atomic number, Z, and r has a value of 1.78 for materials with Z less than 20, but can be extended to Z= 29 with reasonable accuracy. For Z greater than 20, r is equal to 1.75. For the special case of the stopping power of tissue, the parameters are $r_o$=1.80, $a_o$=1.943x10$^{-3}$ and $b_o$=2.273x10$^{-6}$. For all other materials values of a and b are given for each of the r values. In this paper the lower Z materials were of interest as shielding materials, and a curve fit was produced to allow thickness calculation for any material or compound in the range from 1 to 20. Reference 11 coefficients of the range equation are as follows:

| | | r = 1.75 | | r = 1.78 | |
|---|---|---|---|---|---|
| MATERIAL | Z | a | b | a | b |
| | | x10$^6$ | x10$^3$ | x10$^6$ | x10$^6$ |
| Carbon | 6 | 2.58 | 1.2 | 2.33 | 2.0 |
| Aluminum | 13 | 3.10 | 1.9 | 2.77 | 2.5 |
| Iron | 26 | 3.70 | 2.6 | 3.26 | 3.0 |
| Copper | 29 | 3.85 | 2.7 | 3.4 | 3.25 |
| Silver | 47 | 4.55 | 3.7 | | |
| Tungsten | 74 | 5.50 | 4.2 | | |
| Polyethylene | 2.66 | 2.15 | 1.1 | 1.95 | 1.7 |
| Tissue* | 2.32 | 1.2 | 2.11 | 2.0 | 2.0 |
| Water | 3.3 | 2.32 | 1.2 | 2.10 | 2.0 |
| Air | 7.21 | 2.68 | 1.4 | 2.41 | 2.1 |
| Si$_O$ | 10 | 2.87 | 1.7 | 2.58 | 2.5 |

# APPENDIX B
## (Continued)

For r equal to 1.78 the polynomial coefficients were:

For a: $a = A(0) + A(1)Z + A(2)Z^2 + A(3)Z^3$

$A(0)=1.65591$, $A(1)=1.3754\mathrm{x}10^{-1}$, $A(2)=-5.16973\mathrm{x}10^{-3}$,

$A(3)=8.60948\mathrm{x}10^{-5}$

For b: $b = A(0) + A(1)Z + A(2)Z^2 + A(3)Z^3 + A(4)Z^4$

$A(0)=1.67$, $A(1)=1.82981\mathrm{x}10^{-2}$, $A(2)=1.241099\mathrm{x}10^{-2}$,

$A(3)=-9.0232\mathrm{x}10^{-4}$, $A(4)1.817724\mathrm{x}10^{-5}$

The fitted values were compared to the input values, and showed a difference of less than one percent. Note that for compounds or mixtures of elements a weighted value of Z in proportion to their atomic numbers are used to establish range or stopping power.

The range and stopping power can be used to compare the relative shielding requirements in terms of weight per unit area or thickness in feet or other linear unit. The ratio of ranges in grams/cm$^2$ and stopping power in Mev/gm/cm$^2$ were calculated for a number of materials relative to carbon, and for the ranges at 30 Mev and 100 Mev were roughly equal. The relative values of several materials are as follows:

| MATERIAL | DENSITY gm/cm$^3$ | RANGE RATIO TO CARBON | THICKNESS FOR 50GM/CM$^2$ FEET |
|---|---|---|---|
| Carbon | 1.5 | 1.00 | 1.093 |
| Aluminum | 2.65 | 1.19 | 0.736 |
| Water | 1.00 | 0.90 | 2.22 |
| $SiO_2$ | 1.5 | 1.11 | 0.988 |
| Polyethylene | 1.1 | 0.84 | 1.198 |

The ratio of stopping powers is the inverse of the range ratio.

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