NASA Technical Paper 3662

Radiation Analysis for the Human Lunar Return Mission

J. W. Wilson, L. C. Simonsen, J. L. Shinn, and M. Kim
Langley Research Center • Hampton, Virginia

R. R. Dubey and W. Jordan
Old Dominion University • Norfolk, Virginia

National Aeronautics and Space Administration
Langley Research Center • Hampton, Virginia 23681-2199

September 1997

Available electronically at the following URL address: http://techreports.larc.nasa.gov/ltrs/ltrs.html

Printed copies available from the following:

NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 487-4650

Abstract

An analysis of the radiation hazards that are anticipated on an early Human Lunar Return (HLR) mission in support of NASA deep space exploration activities is presented. The HLR mission study emphasized a low cost lunar return to expand human capabilities in exploration, to answer fundamental science questions, and to seek opportunities for commercial development. As such, the radiation issues are cost related because the parasitic shield mass is expensive due to high launch costs. The present analysis examines the shield requirements and their impact on shield design.

Introduction

The Human Lunar Return (HLR) study examined the basic rationale, the required technologies, and the mission development for a return to the Moon. The basic thrust of the HLR mission study is to make humanity a multi-planet society, to open new opportunities for commercialization, and to answer fundamental questions about Earth and solar system science. Since these goals are mainly futuristic in orientation, the attempt is to lay the foundation for human space activity over the next three decades. The near term objectives will hinge mainly on the current cost of space exploration and emphasize the possibility of a low cost return to the Moon. Radiation protection systems (shielding, monitoring, and medical supplies) impact mission cost, and uncertainty in past shield databases is inadequate for the present design study. Recent advances in shield design technologies require a regeneration of the necessary design database (refs. 1 through 6). For example, a progression of aluminum shield attenuation characteristics is shown in figure 1. The lower curve is that generated by the code of Letaw, Silberberg, and Tsao (ref. 1) and was used in the National Council on Radiation Protection (NCRP) report 98 (ref. 7). The nuclear fragmentation (NUCFRG1) curve used the first generation of the Langley Research Center (LaRC) database (ref. 2) and

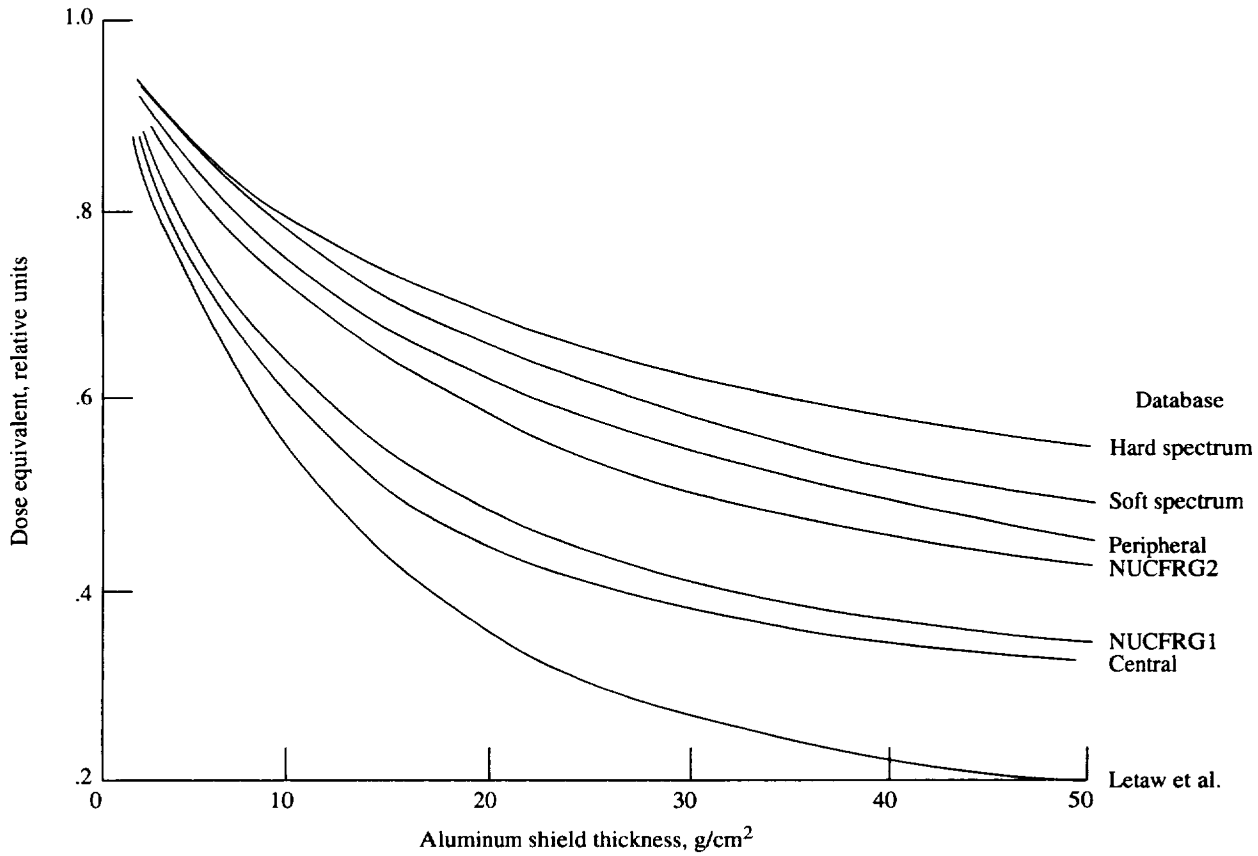

Figure 1. Shield attenuation for solar minimum galactic cosmic ray dose equivalent resulting from nuclear fragmentation (NUCFR) models G1 and G2.

the corresponding first version space radiation transport code (ref. 3). The peripheral and central limits (curves) are the unitary limits on the projectile fragmentation which ensure charge and mass conservation, not including the direct target knockout contributions to the transmitted fluence (ref. 4). The NUCFRG2 (curve) is the revised database that resulted from the 600 A MeV experiments at the Bevalac facility (ref. 5). The two upper curves (labeled *hard spectrum* and *soft spectrum*) include improved nuclear data for the knockout of light fragments from projectile and target nuclei and the uncertainty in their production spectra (ref. 6). These data encompass our best current estimate of the attenuation of dose equivalent in aluminum. Clearly, large changes in the nuclear data and transport procedures have occurred in the last several years. Only the completion of the transport code with the as yet neglected radiation components (with added laboratory and flight testing) will allow a final evaluation of the expected astronaut exposure.

In returning to the Moon, we first note that in addition to great changes in technology, our understanding of space radiation protection practice has improved since the first lunar missions. The Apollo program was recognized as a high risk, exploratory venture in which the radiation risks were a direct trade-off against the other mission risks (ref. 8). As a result, the protection standards were mainly concerned with early biological effects associated with high exposures that may directly impact mission safety. The late biological effects such as cancer induction and cataract formation were of secondary concern. Thus, the low level galactic cosmic rays (GCR) were neglected in the design process. The important solar particle events (SPE) of the time were those of solar cycle 19, including 23 February 1956, 16 July 1959, and 12–13 November 1960, for which it was estimated that serious exposures could impact mission safety, but that early lethality was unlikely. During the Apollo program, between missions 16 and 17, the 4 August 1972 event occurred. This event had significantly higher exposures within typical space structures than prior events, bringing to mind the potential lethality of solar particle events (ref. 9). In addition to an improved knowledge of the environment, the whole texture of the space program changed with the development of the Skylab and shuttle operations, in which access to space became routine, and the need for revised space radiation standards developed (ref. 10). As a result of the routine access to space, the neglect of the galactic cosmic ray background was reevaluated and identified as a critical element in future NASA radiation concerns (ref. 11). No standards have been established to protect astronauts from the high charge and energy (HZE) particles of galactic cosmic rays. In addition to changes in protection practices, the technology base has improved, and mission costs may change radically as the result of new space transportation methods, the use of a space-based staging area (provided by the developing International Space Station), and new spacecraft materials. Such new materials may provide added protection compared with an equal mass of aluminum (the standard construction material in the Apollo program).

In this report, we examine the attenuation characteristics of potential shield materials for use in the early return to the Moon and assess the shield requirements that protect the astronauts.

Radiation Protection Standards

Currently, no radiation limits have been accepted or even recommended for exploration class missions. However, for *planning purposes only,* the National Council on Radiation Protection (NCRP) suggests that the limits established for astronauts in low-Earth orbit (LEO) may be used as guidelines for other missions if the principle of ALARA (as low as reasonably achievable) is followed (ref. 7). LEO exposure limits are currently given as dose equivalents to specific organs for short-term (30-day) exposure, annual exposure, and total career exposure. LEO limits for the skin are 150, 300, and 600 cSv (1 cSv = 1 rem), respectively. LEO limits for the ocular lens are 100, 200, and 400 cSv, respectively. LEO limits for the blood-forming organs (BFO) are 25, 50, and 100 to 400 cSv, respectively (with career limits, depending on age and gender). Note that the exposure limits for the BFO reflect the exposure limitation to prevent all cancer, assuming that the BFO dose is indicative of whole body exposure. The NCRP is currently revising the LEO recommendations as a result of larger estimates of cancer risk coefficients (ref. 12).

The current limits are based on a 3-percent lifetime excess fatal cancer risk, which is comparable to the fatal risk of moderately safe occupations (ref. 7). A lower acceptable risk may be required due to the improved safety record, in recent years, of these moderately safe industries. Furthermore, it is unlikely that special high risk limits for exploratory class missions will be approved in the current social context. In the current context, risk management for Human Lunar Return (HLR) may be even more restrictive and may lead to more stringent, or at best unchanged, shield requirements.

Even if designs are adequate for protection from a solar event, an accidental exposure could occur. In the event of accidental exposure, methods to deal with the potential astronaut health problems must be part of the planning process, and there must be reasonable assumptions as to the worst case scenario to allow for medical treatment plans and to provide adequate dosimetry to diagnose the expected severity for medical intervention during the course of the mission. This planning requires the specification of adequately complex dosimetry systems capable of estimating organ dose rates. Well-established biological response models must be validated for treatment planning in the space environment (ref. 13).

Radiation Environmental Models

For exploration calculations of radiation effects in free space, we use environmental input models and two transport codes. For galactic cosmic ray (GCR) environments, we now use the model of Badhwar and O'Neill (ref. 14). Our earlier work during the Space Exploration Initiative (SEI) time period used the CREME model (ref. 1) for the GCR environment and an earlier version of the HZETRN code that was developed at Langley Research Center (LaRC) (ref. 2). For solar proton event environmental data, we use a variety of inputs: the fluence (time integrated flux) of the four largest flares that have occurred during the last 40 years—February 1956, November 1960, August 1972, and October 1989 (refs. 9, 15, and 16); flux data from the GOES-7 satellite for a series of 1989 flares, including October 1989; and IMP-5 and IMP-6 data for the August 1972 event. In addition, we have inputs of smaller flare data from IMP-7 and IMP-8 satellites.

For the transport of GCR and solar proton events through various materials, LaRC has developed HZETRN and BRYNTRN, respectively. The transport codes and the database are tested in laboratory experiments performed by the Lawrence Berkeley Laboratory and others. Both codes are well-known and are used widely in the radiation community. We also model the effects of biological response and electronic response to the radiation environment for incorporation into the transport code analysis systems.

Our engineering design tools can model various configurations of spacecraft/habitats to determine the shielding that is provided by the structure, the internal and external equipment, and the consumables. Those results, combined with the transport results, will provide us an estimate of the radiation environment within the spacecraft/habitat. Then we can investigate the optimum placement of equipment to minimize parasitic shield requirements. We are currently validating this procedure with detectors onboard the LEWIS spacecraft that will be launched in May 1997 (ref. 17).

Currently, large uncertainties exist in biological response, spacecraft shielding properties, and transport properties of body tissues to HZE (high charge and energy) particles, such as those which comprise the galactic cosmic rays. The uncertainty in astronaut risk to HZE particles consists of the biological response with uncertainties up to a factor of ~5 and to the transport properties of materials with uncertainties up to a factor of ~2 (fig. 1). The NASA Life Sciences Division is funding projects to reduce these factors. Uncertainties in the GCR background environment are estimated to be about 10 to 15 percent, while the solar event spectra are variable, and the appropriate design spectrum is controversial. For this analysis, we will use the 4 August 1972 event as the most hazardous single event for space exposures yet observed.

Statistical Odds of Encountering a Major Solar Proton Event

Although the statistical odds of encountering a major solar proton event such as the February 1956, July 1959, November 1960, August 1972, or October 1989 event is statistically very low, with only 5 *major* events in the last 40 years (probability for a 16-day mission is about 1 in 200). Serious exposures to the crew would occur if no provisions for a major solar event were provided. For example, the 30-day exposure limit of 25 cSv is greatly exceeded by any of these events without special provision. Some have suggested that early lethality may occur within 45 or more days after an extremely intense event. Clearly, such an event cannot be ignored on the basis that it is unlikely. One need only to recall that with a slight change in schedule, either Apollo 16 or Apollo 17 would have encountered the August 1972 event, which is the most important event ever observed with regard to space radiation safety. Furthermore, one must consider the negative impact on the developing space program if adequate provision is not made to protect the astronauts from a potentially debilitating injury.

If the solar particle event can be predicted from solar observation, crew members will have a minimum warning time of 20 minutes before the arrival of energetic particles (ref. 15). The October 1989 flare came in three main pulses and lasted about 10 days (ref. 16). The limiting dose for the October 1989 flare was the 30-day ocular lens dose (assuming LEO limits), which would be reached only 17 hours after receiving warning (assuming that the crew member on the lunar surface was wearing a space suit). In comparison, one extravehicular activity (EVA) shift may last between 6 and 8 hours. For flares such as the October 1989 event, crew members will have a number of hours to seek shelter before any of the 30-day limits are exceeded. These time limits would determine the safe distance for a crew member to venture from the protection of the habitat or storm shelter. For example, during the August 1972 event, the ocular lens limit would have been reached in about 7 to 8 hours (ref. 9).

The time development of the particle fluence can be very different. The February 1956 event delivered its dose within hours. Twenty minutes after the optical flare and radio noise were seen at Earth, energetic particles arrived from the February 1956 event. From the ground-based measurements, the event's intensity was seen to have peaked 30 minutes later, followed by a decay with a mean time of 1 hour (ref. 15). Thus, the entire flare lasted only a few hours. Crew members would have had significantly less time to reach a flare shelter before limits were exceeded (compared with the October 1989 event). The time development of the February 1956 event was also characteristically very different from the other recorded large flares of November 1960 (ref. 15) and August 1972 (ref. 9).

Only minor doses in free space were predicted by space weather forecasters for the August 1972 event; however, it was the largest event ever observed for space exposures. By 0700 Universal time (UT), the accumulated dose at a 1-cm depth was 2.7 cGy, climbing rapidly to 10 Gy over the next several hours (1400 UT). Astronauts (nominally shielded in free space) would have had only ~3.5 hours to reach a storm shelter from the time of particle onset at 1 AU (astronomical unit) to the time that 30-day exposure limits (assuming LEO limits) were exceeded (ref. 9). Clearly, very high levels of exposure can be received in a short time (a few hours) with possibly inadequate warning, leading to the possibility of early radiation syndrome. Some attention needs to be given to the prediction and control of biological effects which could occur during such an accidental exposure (ref. 13).

Radiation Protection From Various Shielding Thicknesses

Estimates of exposures made in 1992 by using the galactic cosmic ray CREME model and the sum of the 1989 flare events (October, September, and August) are substantially different from the exposure estimates of more recent models of the GCR by Badhwar and O'Neill (ref. 14) and the recent reevaluation of the nuclear databases in the HZETRN code (ref. 18). The solar flare results have changed mainly because of reevaluation of the particle fluence. New tables for GCR exposures behind regolith and polyethylene shields are shown in tables 1 and 2 for solar minimum and maximum, respectively.

Overall, the dose and the dose equivalent are substantially higher because the CREME model underestimated the fluence of important components (ref. 14). In addition to the more intense environmental model, the cross sections for fragmentation and particle production are substantially greater than those represented in prior codes (fig. 1). Also, the atomic interactions are more accurately accounted for than in the Letaw, Silberberg, and Tsao procedure (ref. 1) and in Wilson and Badavi (ref. 19). All these factors compound to increase the estimated astronaut exposure with the latest values given in tables 1 and 2. A factor-of-three reduction in exposures is seen near solar maximum for moderate-to-thin shielding. This ratio of solar minimum to solar maximum decreases to slightly over two at large depths.

We have recalculated the dose and the dose equivalent for the solar particle event of 4 August 1972 with the BRYNTRN code. The results are presented in table 3. We have used two representations of the 4 August 1972 event spectra: one prepared by King (ref. 20) and the other by Wilson and Denn (ref. 9). The relative advantage of a hydrogenic polymer, as opposed to regolith, is clearly apparent in the table. The geometry used is a spherical shell with a tissue sample within a 0-cm and a 5-cm radius. Reducing the values by a factor of 2 approximates self-shielding provided by the human geometry for the skin or lens (0 cm) or the BFO (5 cm). These values are in reasonable agreement with the older values by Simonsen, Nealy, Sauer, and Townsend (ref. 16) and are in good agreement with Wilson and Denn for polyethylene (ref. 9). Doses to the lens or to the skin on the lunar surface are further reduced to about a factor of 4 smaller than the 0-cm values, and the BFO is about a factor of 4 smaller than the 5-cm value given in table 3.

Galactic Cosmic Ray Dosage for 16-Day Exploration Missions

Compared with the other inherent risks of spaceflight, the risks of a 16-day exposure to galactic cosmic rays would not be a concern. We use the following assumptions in estimating GCR exposure:

- 6 days in free space and 10 days on the lunar surface
- 5 g/cm^2 aluminum shield typical of Apollo-type spacecraft
- estimate of blood-forming organ dose as 5-cm water depth dose

The GCR dose estimate would be 1.3 to 3.4 cSv to the skin and 1 to 2.4 cSv to the BFO when the range of values depends on whether the mission is at solar maximum or solar minimum. (Using a computerized anatomical man model would lower these estimates, but the developing transport database will increase the estimates.) These estimates could be compared with the annual allowed exposure of 50 cSv or the 30-day allowed exposure of 25 cSv used for the space station, although these limits do not apply strictly for these radiations. If the mission is planned for 2001, the environment will be near solar maximum, and the minimum GCR environment is appropriate.

Crew Dosage Expected on Lunar Missions During Past Solar Proton Events

The October 1989 event was a series of particle increases lasting 10 days. Exposure estimates (ref. 16) for the October 1989 event during the 3-day trip to or from the Moon, behind a shield thickness of 2 cm of water (lightly shielded module) in free space is between 65 and 80 cSv to the blood-forming organ (BFO) (by using a 5-cm depth dose as the estimated BFO exposure). By using the same assumptions for a 10-cm water shield (typical of a storm shelter), the dose equivalent to the BFO is estimated to be between 10 and 17 cSv. For a lunar surface stay, assuming a 2-cm water shield for the entire 10-day fluence, in which the lunar surface provides additional protection, the estimated BFO dose equivalent is 50 to 65 cSv. For 10 cm of water shielding on the lunar surface for the 10 days, the estimated dose equivalent to the BFO is 8 to 14 cSv. The shielded volumes are assumed to be cylindrical.

In estimating the dose equivalent to the BFO, the lens, and the skin for the August 1972 event, we have used self-shielding factors which substantially reduce the organ dose by about a factor of 2 and an average quality factor of 1.3 (ref. 9). In addition, there is a further reduction on the lunar surface to a factor of 2 because of the lunar shadow. The dose equivalent from the August 1972 event is somewhat higher and is accumulated over a shorter period of time (about 10 to 16 hours). During the three-day transit time, the August 1972 event would result in exposures within a simple pressure vessel (approximately 1 g/cm^2 equivalent water) of 15.6 Sv (skin and lens) and 2.2 Sv (BFO). By moving into an equipment related area (5 g/cm^2 equivalent water, compared to the Apollo command module of 4.5 g/cm^2), the exposures are 2 Sv (skin and lens) and 0.46 Sv (BFO). To meet the 30-day limit, one will require a storm shelter (about 10 g/cm^2) in which 0.6 Sv (skin and lens) and 0.2 Sv (BFO) would have been received.

In a space suit on the lunar surface, the accumulated exposure is about 13 Sv (skin and lens) and 1.1 Sv to the BFO. Moving into a simple pressure vessel on the surface (minimum habitat wall of approximately 1 g/cm^2) reduces the estimated exposures to 7.8 Sv (skin and lens) and 0.85 Sv (BFO). The exposures in an equipment room (5 g/cm^2) within the habitat are still lower, yielding 1 Sv (skin and lens) and 0.23 Sv (BFO), which satisfy the 30-day exposure limitation requirements for the LEO exposure limits.

Using the ALARA principle (keeping exposure as low as reasonably achievable), one would attempt to provide as much shielding as reasonably possible. The following requirements are necessary to meet currently accepted space station limits as applied to this mission:

- a storm shelter of at least 10 g/cm^2 of water equivalent shield during transit to the Moon (note that this is equivalent to about 14 g/cm^2 of aluminum)
- a region that has at least 5g/cm^2 water equivalent shielding (7 g/cm^2 of aluminum) that all astronauts can reach in a timely fashion (within a few hours) during lunar operations
- improved biological understanding that could possibly relax the current 30-day limit, result in great reductions in the shield requirements, and reduce mission costs
- exploration of dynamic shielding concepts in which movable equipment and materials can be used to make the most effective temporary use of onboard mass

Radiation Protection Properties of Materials

The GCR background during a 16-day mission is not more than 3.4 cSv. The primary protection problem for the HLR is that the possibility of solar particle event exposures may be quite large, with a 0.5-percent probability within a 16-day mission. Although the probability of occurrence is small, the potentially serious illness which could result is a cause for concern. There are two important parameters in determining space shield properties in a solar particle event: stopping the low energy protons by atomic collision, and to a lesser extent, stopping the production of particles in collision with the shield nuclei. In both respects, hydrogen is a preferred material constituent; the higher the hydrogen content per unit mass of material, the better the shield properties (both the atomic and nuclear properties). Thus, polyethylene, other polymers, water, compressed methane (a possible rocket fuel), and LiH are all good materials. Shield attenuation results are shown in table 4 for several materials for the October 1989 event (ref. 16). Of the materials listed, only the regolith contains no hydrogen-bearing molecules. Water and magnesium hydride are likely materials for life support systems. Polyethylene is used as a high performance shield and shows significant advantage over regolith. Adding boron to the polyethlene to deplete the low energy (thermal) neutrons appears to be counterproductive because the added production of secondaries and the change in the atomic cross sections usually increase the dose. Lithium hydride is probably a better alternative.

Protecting the astronaut from space radiation is dependent on the local distribution of materials. Much protection will be derived from materials and equipment that is onboard the spacecraft for other purposes. The choice of materials used to construct the spacecraft systems is very important, and some attention should be given to materials that will be used in future spacecraft technology. For example, materials designed primarily for water and food storage also could be useful for other purposes. Removable polymeric flooring and other equipment could be temporarily rearranged for protection from a solar event. Parasitic shielding is expensive, but polyethylene is a good material if added shield material is required. However, polyethylene has limited material properties and poses a flammability issue that must be resolved. Polymer composites are the next most useful materials, but the preferred material would have a high binder-to-fiber ratio to maintain a high hydrogen content. Careful consideration should be given to the other onboard materials.

Concluding Remarks

For the short-term missions to the Moon, the shielding against the galactic cosmic ray (GCR) background is negligible. Longer missions (to establish a permanent base) will be limited by the GCR exposures, and the latest results on shielding properties will require added shield mass over prior estimates. The solar energetic particle events require special consideration and protection of at least 10 g/cm^2 of water or polyethlene during transit to the Moon and 5 g/cm^2 on the Moon's surface. The shield mass requirements to protect astronauts from a solar event are about 40 percent higher if regolith or aluminum is used. In the event of an accidental exposure by a solar event, some provision for medical treatment needs to be provided. The accurate prediction of accidental exposure levels is necessary to allow proper prognosis and medical treatment. Appropriate design criteria for protection against solar events are still lacking.

NASA Langley Research Center
Hampton, VA 23681-2199
May 6, 1997

References

1. Letaw, J. R.; Silberberg, R.; and Tsao, C. H.: Radiation Hazards on Space Missions Outside the Magnetosphere. *Adv. Space Res.*, vol. 9, no. 10, 1989, pp. 285–291.
2. Wilson, John W.; Townsend, Lawrence W.; and Badavi, F. F.: A Semiempirical Nuclear Fragmentation *Model. Nucl. Instrum. & Methods Phys. Res.*, vol. B18, no. 3, Feb. 1987, pp. 225–231.
3. Wilson, John W.; Townsend, Lawrence W.; and Badavi, Forooz F.: Galactic HZE Propagation Through the Earth's Atmosphere. *Radiat. Res.*, vol. 109, no. 2, Feb. 1987, pp. 173–183.
4. Townsend, L. W.; Cucinotta, F. A.; and Wilson, J. W.: HZE Reactions and Data-Base Development. *Biological Effects and Physics of Solar and Galactic Cosmic Radiation*, C. E. Swenberg, G. Horneck, G. Stassinopoulos, eds., Plenum Press, 1993, pp. 787–809.
5. Wilson, J. W.; Shinn, J. L.; Townsend, L. W.; Tripathi, R. K.; Badavi, F. F.; and Chun, S. Y.: NUCFRG2: A Semiempirical Nuclear Fragmentation Model. *Nucl. Instrum. Phys. Res. B*, vol. 94, 1994, pp. 95–102.
6. Cucinotta, F. A.; Townsend, L. W.; Wilson, J. W.; Shinn, J. L.; Badhwar, G. D.; and Dubey, R. R.: Light Ion Components of the Galactic Cosmic Rays—Nuclear Interactions and Transport Theory. *Adv. Space Res.*, vol. 17, no. 2, 1996, pp. (2)77–(2)86.
7. National Council on Radiation Protection and Measurements: Guidance on Radiation Received in Space Activities. NCRP Rep. No. 98, July 31, 1989.
8. Billingham, John; Robbins, Donald E.; Modisette, Jerry L.; and Higgins, Peter W.: *Status Report on the Space Radiation Effects on the Apollo Mission. Second Symposium on Protection Against Radiations in Space*, Arthur Reetz, Jr., ed., NASA SP-71, 1965, pp. 139–156.
9. Wilson, J. W.; and Denn, F. M.: *Preliminary Analysis of the Implications of Natural Radiations on Geostationary Operations.* NASA TN D-8290, 1976.
10. National Academy of Science: *Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems.* NAS Rep. CR-128872, 1970.
11. Grahn, Douglas, ed.: *HZE-Particle Effects in Manned Spaceflight.* NAS, 1973.
12. Smith, H., ed.: *1990 Recommendations of the International Commission on Radiological Protection.* ICRP Publ. 60, Nov. 1990.
13. Wilson, J. W.; Cucinotta, F. A.; Jones, T. E.; and Chang, C. K.: *Astronaut Protection From the 4 August 1972 Solar Event.* NASA TP-3643, 1997.
14. Badhwar, G. D.; and O'Neill, P. M.: Galactic Cosmic Radiation Model and Its Applications. *Adv. Space Res.*, vol. 17, no. 2, 1996, pp. (2)7–(2)17.
15. Foelsche, Trutz; Mendell, Rosalind B.; Wilson, John W.; and Adams, Richard R.: *Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes; Relevance to SST Operations and Space Research.* NASA TN D-7715, 1974.
16. Simonsen, Lisa C.; Nealy, John E.; Sauer, Herbert H.; and Townsend, Lawrence W.: *Solar Flare Protection for Manned Lunar Missions: Analysis of the October 1989 Proton Flare Event.* SAE Tech. Paper Ser. 911351, July 1991.

17. Shinn, J. L.; Cucinotta, F. A.; Wilson, J. W.; Badhwar, G. D.; O'Neill, P. M.; and Badavi, F. F.: Effects of Target Fragmentation on Evaluation of LET Spectra From Space Radiation in Low-Earth Orbit (LEO) Environment—Impact on SEU Predictions. *IEEE Trans. Nucl. Sci.*, vol. 42, no. 6, pt. 1, Dec. 1995, pp. 2017–2025.

18. Wilson, John W.; Badavi, Francis F.; Cucinotta, Francis A.; Shinn, Judy L.; Badhwar, Gautam D.; Silberberg, R.; Tsao, C. H.; Townsend, Lawrence W.; and Tripathi, Ram K.: *HZETRN: Description of a Free-Space Ion and Nucleon Transport and Shielding Computer Program.* NASA TP-3495, 1995.

19. Wilson, John W.; and Badavi, F. F.: Methods of Galactic Heavy Ion Transport. *Radiat. Res.*, vol. 108, 1986, pp. 231–237.

20. King, Joseph H.: Solar Proton Fluences for 1977-1983 Space Missions. *J. Spacecr. & Rockets*, vol. 11, no. 6, June 1974, pp. 401–408.

Table 1. Annual Dose (*D*) and Dose Equivalent (*H*) for Galactic Cosmic Rays Behind Slab Shield Amounts (*x*) at the 1977 Solar Minimum

Lunar regolith, x, g/cm^2	D, cGy/yr for—		H_{60}, cSv/yr for—	
	0 cm	5 cm	0 cm	5 cm
0	19.44	20.41	120.13	94.63
1	21.92	20.37	132.26	91.06
2	22.20	20.33	126.62	87.76
5	22.25	20.17	111.38	79.43
10	21.94	19.91	93.74	69.36
25	20.93	19.20	68.66	53.89
50	19.46	18.10	56.32	45.78
75	18.05	16.99	52.54	43.21

Polyethylene, x, g/cm^2	D, cGy/yr at—		H_{60}, cSv/yr at—	
	0 cm	5 cm	0 cm	5 cm
0	19.44	20.41	120.13	94.63
1	20.52	20.18	118.39	88.63
2	20.39	19.96	108.86	83.33
5	19.71	19.40	86.61	70.78
10	18.79	18.69	64.09	57.30
25	17.27	17.38	38.92	41.18
50	15.84	15.88	30.82	35.20
75	14.45	14.38	28.18	32.43

Table 2. Annual Dose (*D*) and Dose Equivalent (*H*) for Galactic Cosmic Rays Behind Slab Shield Amounts (x) at the 1970 Solar Minimum

Lunar regolith, x, g/cm^2	D, cGy/yr at—		H_{60}, cSv/y at—	
	0 cm	5 cm	0 cm	5 cm
0	6.12	6.97	37.90	34.47
1	7.21	7.02	44.01	33.66
2	7.44	7.06	43.33	32.87
5	7.74	7.15	40.55	30.72
10	7.93	7.24	36.42	27.84
25	8.04	7.36	28.98	22.80
50	7.94	7.37	24.77	20.02
75	7.72	7.25	23.76	19.43

Polyethylene, x, g/cm^2	D, cGy/yr at—		H_{60}, cSv/yr at—	
	0 cm	5 cm	0 cm	5 cm
0	6.12	6.97	37.90	34.47
1	6.63	6.94	39.09	32.77
2	6.69	6.90	37.07	31.21
5	6.66	6.80	31.40	27.25
10	6.51	6.66	24.51	22.59
25	6.23	6.41	15.36	16.47
50	6.03	6.16	12.35	14.39
75	5.77	5.83	11.69	13.71

Table 3. Dose (*D*) and Dose Equivalent (*H*) for 4 August 1972 Event Spectra by King and LaRC

Lunar regolith, x, g/cm^2	*D*, cGy King		*H*, cSy King		*D*, cGy LaRC		*H*, cSy LaRC	
	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm
1	3250.5	242.55	5696.6	332.73	2613.7	254.1	4491.4	346.57
2	1722.2	183.48	2843.8	251.55	1472.7	198.02	2391.3	269.98
5	495.2	86.0	772.5	119.0	480.84	100.66	740.36	137.84
10	117.2	29.10	179.7	41.3	132.59	38.20	200.75	53.57
25	6.08	2.39	11.27	4.69	9.34	3.96	16.04	6.91
50	0.2932	0.23	1.42	0.95	0.5	0.35	1.79	1.92
75	0.0732	0.083	0.5232	0.39	0.099	0.12	0.61	0.47

Polyethylene, x, g/cm^2	*D*, cGy King		*H*, cSy King		*D*, cGy LaRC		*H*, cSy LaRC	
	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm	0 cm	5 cm
1	2437.4	221.82	3714.4	322.20	2013.4	234.63	3022.5	338.18
2	1188.7	155.5	1727.9	225.36	1055.0	170.84	1515.8	245.76
5	287.4	60.41	401.09	88.0	295.83	73.48	410.2	106.09
10	55.31	16.1	76.14	24.44	67.96	22.55	93.77	33.54
25	1.96	0.874	3.27	2.03	3.33	1.56	5.20	3.09
50	0.125	0.0898	0.36	0.367	0.18	0.13	0.49	0.47
75	0.04	0.0317	0.13	0.13	0.054	0.04	0.16	0.17

Table 4. Dose (D) and Dose Equivalent (H) for 1989 Large Solar Particle Events Behind Slab Shield Amounts (x)

Material	x, g/cm^2	D, cGy		H_{ICRP26}, cSv	
		0 cm	5 cm	0 cm	5 cm
Lunar regolith	1	3761.76	208.09	7435.22	306.24
	2	1586.95	163.96	2792.31	239.48
	5	391.73	88.28	615.87	127.24
	10	109.88	39.65	164.00	57.03
	25	13.67	7.66	20.71	11.68
	50	1.75	1.22	3.13	2.24
	75	0.40	0.32	0.89	0.70
Water	1	2830.31	198.52	5099.28	291.77
	2	1176.81	150.11	1922.11	218.56
	5	276.48	73.68	411.37	105.56
	10	73.68	30.07	105.56	42.88
	25	8.22	4.90	12.00	7.29
Magnesium hydride	1	3286.85	204.37	6166.85	300.69
	2	1383.24	157.76	2336.36	230.15
	5	333.30	81.26	508.18	116.74
	10	91.02	34.93	132.66	49.99
	25	10.89	6.28	16.19	9.45
Polyethylene	1	2587.62	195.67	4552.52	287.47
	2	1065.36	145.79	1706.01	212.10
	5	245.81	69.35	360.31	99.23
	10	64.21	27.42	90.89	39.05
	25	6.91	4.23	10.02	6.30
Borated polyethylene	1	2957.96	201.52	5346.73	296.48
	2	1239.37	153.69	2029.53	224.13
	5	295.16	76.87	439.73	110.38
	10	79.37	31.96	113.69	45.72
	25	9.03	5.35	13.18	7.99
Lithium hydride	1	2822.50	199.70	4979.57	294.08
	2	1184.89	151.50	1903.08	221.22
	5	282.09	74.90	415.17	107.75
	10	75.67	30.71	107.58	43.97
	25	8.49	4.99	12.27	7.39

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1997

3. REPORT TYPE AND DATES COVERED
Technical Paper

4. TITLE AND SUBTITLE
Radiation Analysis for the Human Lunar Return Mission

5. FUNDING NUMBERS
WU 199-45-16-11

6. AUTHOR(S)
J. W. Wilson, L. C. Simonsen, J. L. Shinn, R. R. Dubey, W. Jordan, and M. Kim

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-17613

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TP-3662

11. SUPPLEMENTARY NOTES
Wilson, Simonsen, and Shinn: Langley Research Center, Hampton, VA; Dubey and Jordan: Old Dominion University, Norfolk, VA; Kim: NRC-NASA Resident Research Associate at Langley Research Center, Hampton, VA.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified–Unlimited
Subject Category 92
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An analysis of the radiation hazards that are anticipated on an early Human Lunar Return (HLR) mission in support of NASA deep space exploration activities is presented. The HLR mission study emphasized a low cost lunar return to expand human capabilities in exploration, to answer fundamental science questions, and to seek opportunities for commercial development. As such, the radiation issues are cost related because the parasitic shield mass is expensive due to high launch costs. The present analysis examines the shield requirements and their impact on shield design.

14. SUBJECT TERMS
Human Lunar Return; Radiation protection; Solar particle events; Galactic cosmic rays; Shield design

15. NUMBER OF PAGES
15

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102