OPTIMIZATION SHIELD MATERIALS TRADE STUDY FOR LUNAR/GATEWAY MISSION

R.K. Tripathi[1], J.W. Wilson[1], F.A. Cucinotta[2], B. M. Anderson[1] and L.C. Simonsen[1]

[1]*NASA Langley Research Center, Hampton, VA, USA*
[2]*NASA Johnson Space center, Houston, TX, USA*

ABSTRACT

The great cost of added radiation shielding is a potential limiting factor in many deep space missions. For this enabling technology, we are developing tools for optimized shield design over multi-segmented missions involving multiple work and living areas in the transport and duty phase of various space missions. The total shield mass over all pieces of equipment and habitats is optimized subject to career dose and dose rate constraints. Preliminary studies of deep space missions indicate that for long duration space missions, improved shield materials will be required. The details of this new method and its impact on space missions and other technologies will be discussed. This study will provide a vital tool for evaluating Gateway designs in their usage context. Providing protection against the hazards of space radiation is one of the challenges to the Gateway infrastructure designs. We will use the mission optimization software to scope the impact of Gateway operations on human exposures and the effectiveness of alternate shielding materials on Gateway infrastructure designs. It is being proposed to use Moon and the Lagrange points as the hub for deep space missions. This study will provide a guide to the effectiveness of multifunctional materials in preparation to more detailed geometry studies in progress.

INTRODUCTION

Shield mass can be a high-cost factor in system designs for the long-term operations required in deep space operations and optimization methods in the design process will be critical to cost-effective progress in space development (Tripathi and Wilson et al., 2002). Limiting the time of transfer to duty station or the mission time within the solar cycle as well as the choice of materials used in construction can reduce the shield mass required on specific missions (Tripathi and Shinn et al., 2001). Such a procedure is adequate for shield design for a space exploratory mission or a space tourist. Unfortunately, requirements for the career crew operating a transportation infrastructure are quite different since an astronaut will enter service and have missions once or twice a year over a ten-year career. In this case, the shield design process is very different.

Much of the protection within a space structure is provided by the structural elements, onboard materials, and equipment required for other purposes and the means of making the best choice of materials among various options is critical to the protective qualities of the overall design. Multifunctional materials (for example, structural elements that have good shielding properties) will be common in the optimization process. Furthermore, the design decisions cannot be made in a vacuum and multidisciplinary design methods need to be developed. The need for multifunctional/multidisci-plinary design techniques was identified as critical to the cost-effective development of space several years ago and expanded on recently (Tripathi and Shinn et al., 2001).

In the past an amount of exposure was assigned to each mission segment and developed as a subjective strategy with relative improvements of costs through material trades dependent on off-optimum design solutions. In this study, the optimization method for minimum mass determination is used in performing trade studies to enable objective trade reduction costs since strategies for meeting exposure constraints are optimized over the entire mission architecture for each trade. In addition to optimized design trades, we will also consider the implementation of the principle of as low as reasonably achievable (ALARA) required by federal regulation and normally ignored in mission design studies. The ALARA principle will be met by added protection of the crew quarters where members will spend a significant fraction of each day sleeping. The main crew quarter design will also be used as the shelter from potential solar particle events during the mission. In this respect, we assume an adequate strategy for exposure limitation during extra vehicular activity (EVA) is available and the design is mainly the habitable volume and crew quarter/SPE shelter. Emergency planning in the case of an accidental SPE exposure will have to be part of the overall mission plan and is not considered in the present study.

In the present study, we will consider two singular baseline missions, a 47 day Lunar mission, a baseline 62 day L1 mission to a deep space platform assuming Al 2219 as the reference construction material. Two multiuse infrastructure operation missions are considered, 30-day lunar missions and 37-day L1 missions (e.g., telescope). Trades on materials for construction of the living/working space and crew quarter shielding and impact on costs through a change in launch mass will be used to quantify the savings. In addition to the material trade studies, propulsion engine trade studies can be performed by change in mission scenario time lines.

EXPOSURE AND OTHER CONSTRAINTS

The present exposure constraints used in the space program are recommended for low Earth orbit (LEO) operations by the National Council on Radiation Protection (NCRP report 98, 1989) and approved by the NASA Administrator and OSHA. There are no limits for deep space operations due to the unusual composition of the GCR and the resultant uncertainties in associated health risks. The NCRP did recommend that the limits for low earth orbit (LEO) operations could be used as a guide in deep space operational studies. New exposure recommendations are now approved by the NCRP (NCRP report 132, 2001) and the new LEO limits are given for the three critical organs of skin, ocular lens, and blood forming organ (BFO) and will be used herein recognizing the associated uncertainties. We use dose equivalent for the Gy-Eq since insufficient data will not allow Gy-Eq evaluation at this time (Tripathi. and Wilson, et al.).

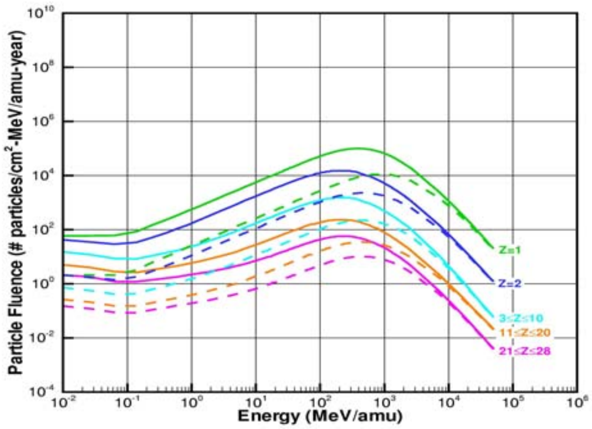
In the present work, the optimized mission will be taken as the minimum mass to meet mission requirements and not exceed the exposure constraints in tables 1 and 2. The present design considerations are for the main habitable areas. The volume limited crew quarters where a large fraction of personal time is spent will have added protection to further reduce exposures (ALARA) and will also be designed to provide the shelter from a solar particle event.

Aside from the radiation health risks, the psychological well being and its impact on crew performance also affects the shield design (Woodward et al., 1997). Crew performance level is related in part to the length of the mission and the volume of the work/living areas of the spacecraft. The design performance levels of Optimal, Performance Limit, and Tolerable are shown in Figure 1 as a function of duration of the stay. Rather small volumes are useful over short time periods but long missions require sufficient space for a crew to perform at reasonable levels. We will use the Optimal design for the habitable volume and the Tolerable design for the crew quarters which will also serve as the SPE shelter.

SPACE ENVIRONMENT AND SHIELDING MATERIALS

In order to quantify radiation exposure in space, it is required that the external ambient ionizing radiation environment be specified in terms of individual constituents and their respective energy fluxes. A great quantity of observational space environmental data from instrumented space platforms has been amassed in recent decades and used in developing computer models serving to define, as well as possible, the composition and temporal behavior of the space environment (Badhwar and O'Neill, 1992). From the standpoint of radiation protection for humans in interplanetary space, the heavy ions (atomic nuclei with all electrons removed) of the galactic cosmic rays (GCR) and the sporadic production of energetic protons from large solar particle events (SPE) must be dealt with. The GCR environmental model used herein is based on a current version in which ion spectra are modulated between solar maxima and minima according to terrestrial neutron monitor data assuming the radial dependent diffusion model of Badhwar and Atwell, et al. 1997. The modeled spectra for solar minimum in 1977 and Solar Maximum in 1990 as given by Badhwar are shown in Figure 1.

The environment near a large celestial body is modified by interaction with local materials producing an induced environment and shielding within the subtended angle of such a large body. The surface exposure on a lunar plain is shielded below the horizon but experiences an induced environment (mainly but not exclusively neutrons) produced in the local surface. The lunar surface GCR environment is shown in Figure 4 at the 1977 Solar Minimum and the 1990 Solar Maximum. In addition to the GCR ions streaming from overhead, large



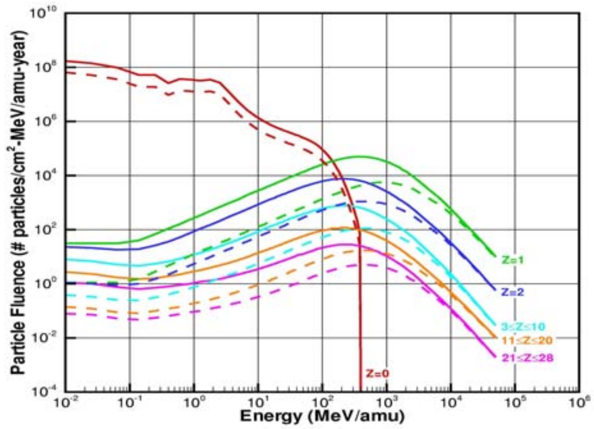


Fig. 1. GCR spectra at the 1997 Solar Minimum (full lines) surface
and 1990 Solar Maximum (dashed lines)

Fig. 2: Legend as in Figure 1 at the Lunar

numbers of neutrons are produced in the lunar surface materials and diffuse from below the surface as shown in the Figure 2.

Large SPE have only been observed to occur during times of increased solar activity conditions, and very large energetic events of grave important to human protection occur only infrequently (avg. 1 or 2 per cycle) and only outside of two years of solar minimum. Among the large events, the largest observed ground level event of the last 60 years of observation is that of February 23, 1956 which produced a 3600 percent increase in neutron monitor levels on the terrestrial surface. The next largest event observed is the September 29, 1989 event with ground level increases of 400 percent or an order of magnitude smaller than that of Feb. 1956 event. Numerous other ground level events of smaller magnitude have occurred but are a factor of four and more lower in magnitude than the Sept. 1989 event. It is known that large SPEs are potentially mission threatening, and astronauts in deep space must have access to adequate shelter from such an occurrence. The SPE particle energy spectrum used here has been derived from the event, which took place on September 29, 1989. To provide a baseline worst-case scenario we assume an event of the order of four times larger than the September 29, 1989 event as an event comparable to the August 4, 1972 event from the point of view of space exposure. The September 1989 SPE spectrum is shown in Figure 3. If we meet 30-day dose rate constraints on an event four times larger than the September 1989 event then it is unlikely that an added factor of two or so larger events (like that of Feb. 23, 1956) would have serious medical consequences.

The SPE are likewise altered by the presence of a large body similar to the GCR. The corresponding lunar surface environment is shown in Figures 4. The role of the neutrons on the lunar surface is less effective in causing exposure relative to the protons streaming from overhead. Note that is in contrast to the more energetic GCR wherein large numbers of neutrons are produced in the lunar surface materials (see Figure 2).

The effectiveness of a given shield material is characterized by the transport of energetic particles within the shield, which is in turn defined by the interactions of the local environmental particles (and in most cases, their secondaries) with the constituent atoms and nuclei of the shield material. These interactions vary greatly with different material types. Materials in the present study are aluminum, polyetherimide, polysulfone, polyethelene, lithium hydride, liquid methane, graphite nanofibers and liquid hydrogen. For space radiation shields, materials with high hydrogen content generally have greater shielding effectiveness, but often do not possess qualities that lend themselves to the required structural integrity of the space vehicle or habitat. Organic polymers are the exception. The design of properly-shielded spacecraft and habitats for long-duration human presence in interplanetary space will thus require an approach tending toward optimization of a compromise between protective shielding and various other functional aspects of the onboard materials. Candidate multifunctional materials for such an optimization approach have been chosen here to represent various contributing elements in a vehicle shield design. Liquid hydrogen and methane are possible fuels that in large quantities may contribute substantially to overall protection. Aluminum has long been a spacecraft material of choice although various forms of polymeric materials show enhanced protection properties such as polyethylene. The polysulfone and polyetherimide are high performance structural polymers. Lithium hydride is a popular shield material for nuclear power reactors, but is generally not useful for other functions. The graphite nanofiber materials heavily impregnated with hydrogen may well represent a viable multifunctional component in future space structures, and its inclusion here should presently be considered as not yet state-of-the-art. The results of detailed transport calculations for these materials have been incorporated into a shield design database.

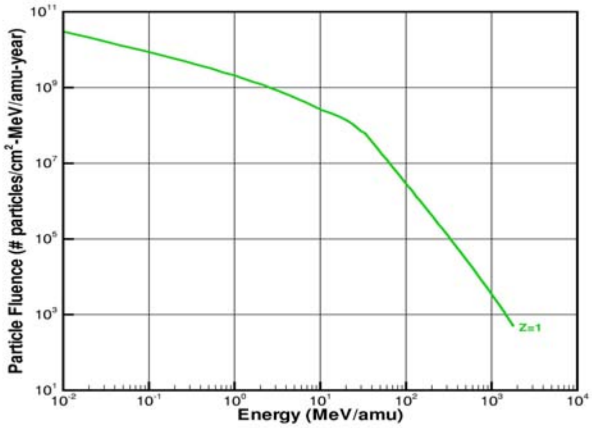


Fig. 3. SPE spectrum during September 1989 as observed near Earth.

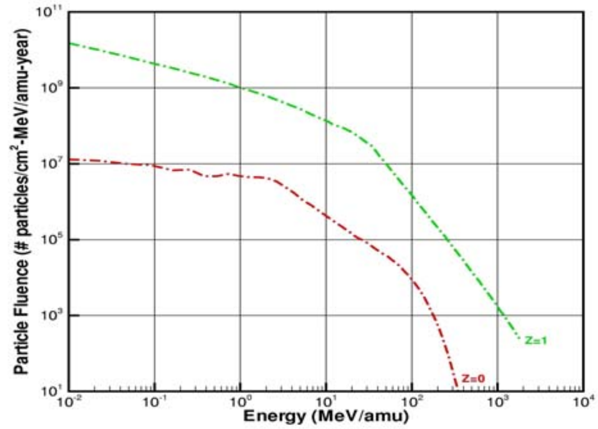


Fig. 4. The Lunar surface environment during September 1989

CONSTRAINTS AND OPTIMIZATION

The general principles required to optimize a mission is as follows. For example, a mission to the L1 in three segments (Earth to L1 trip in time T_1, time on duty of T_2, and return trip of duration T_3) would first have to meet a requirement similar to

$$R_j(x_1)\, T_1 + R_j(x_2)\, T_2 + R_j\, (x_3)\, T_3 + H_{spe}(x_{spe}) < L_j \tag{1}$$

where x_i is the shield thickness of the ith segment of the mission and L_j is the exposure limitation. The thirty-day and annual dose rate constraints must be applied over each mission segment where the SPE drives the crew quarter shield design. We assume $x_1 = x_3$ for missions in which the transport vehicle is common to both transport segments with corresponding assumptions on required mass. The L_j is the accepted exposure limit to the j^{th} critical organ defined for LEO operations. Note, x_i, i = 1-3 are greater than 1 g/cm^2 in order to meet micrometeoroid impact requirements. Note, the above prescription does not account for the ALARA principle. Herein, the shelter is assigned to be the sleep quarters as one form of ALARA. There are many combinations of x_1, x_2, x_3 and x_{spe} which satisfy the constraints above so that one must optimize the shielding by minimizing the total shield mass subject to the above constraints as follows:

$$\text{Min}\{V_s(x_1) + V_s(x_2) + V_s(x_3) + V_s(x_{spe})\}\ .\ \rho = M_m \tag{2}$$

where V_s is the shield volume of each mission segment associated with the required living volume of optimum performance or the crew quarter/shelter as appropriate. Note, $V_s(x_3)$ is set zero if the same transport vehicle is used in segments 1 and 3.

SINGULAR MISSION ARCHITECTURE

L2 Singular Mission

There are several possible missions to L2 for not only space science but as a possible gateway to deep space exploration to asteroids or Mars. A reference profile for a singular L2 mission is for 18 days in transit from and back to LEO with a 26-day mission stay. The crew size is taken as four members with careers in midlife (40 years of age). The trip begins on January 1 2014. The falls outside of two years of Solar minimum and SPE is expected to occur. As a result, additional shielding is required for safe shelter and that brings the differential as shown in Figure 5.

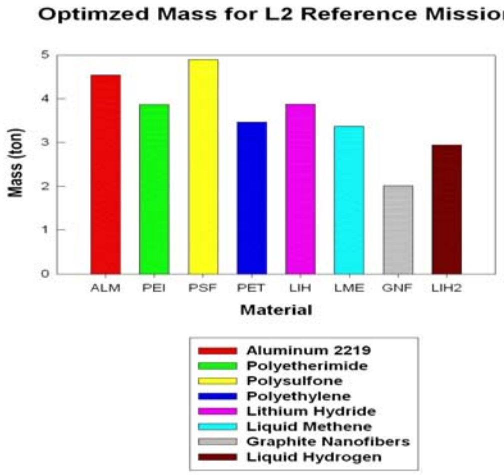


Fig. 5. Optimized mass for L2 reference and trade missions for various materials.

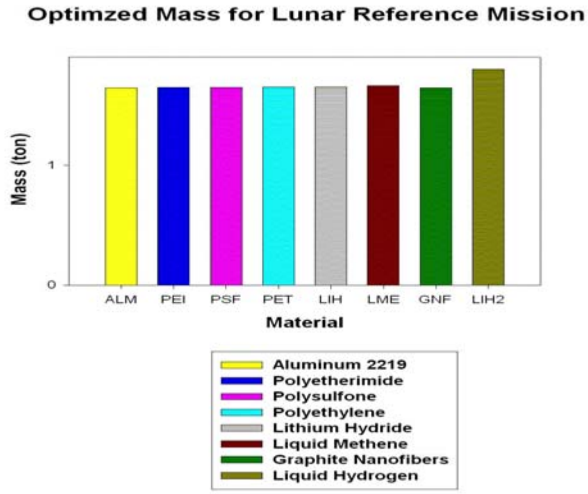


FIG. 6. Optimized mass for Lunar reference and trade missions for various materials.

Lunar Singular Mission

The lunar singular mission profile will be taken as a 4.5-day transit to an L1 with a 2-day layover followed by a 2-day trip to the lunar surface. The surface stay is for 30 days followed by a 2-day return to L1 with a second 2-day layover followed by a 4.5-day return to LEO. The trip begins on March 3, 2018 near solar minimum. The crew size is taken as four middle aged men and women of equal numbers. The optimized reference profile is given in reference 1. Note there are several pieces of equipment involved in this scenario, which affects the overall mass. This mission falls within two years of solar minimum and no SPE is expected to occur. Only minimum shielding is required and material type plays no role as shown in Figure 6. The small differences in shield mass is due to the differences in geometry resulting from different densities of the shielding materials.

GATEWAY INFRASTRUCTURE

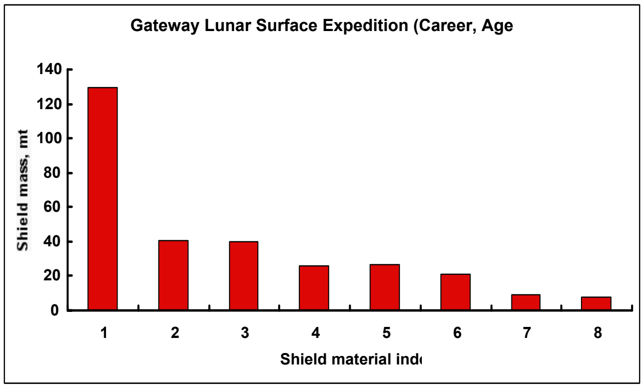
The Gateway infrastructure (Tripathi and Wilson et al., 2001) is described elsewhere and provides a transportation network for near Earth missions but also a staging area for deep space exploration. The transportation infrastructure is assumed to be operated by career astronauts as a service to exploration and development of space including commercialization. Inherent in the assumptions made by the NCRP in arriving at the LEO career dose limits in tables 1 and 2, is that the astronaut will have a ten year career starting at a specified age (NCRP report 98, 1989 and report 132, 2001). We assume herein that the astronaut will perform two trips a year throughout a ten year career or a total of 20 trips. The career exposure constraint is then written as

$$20 \int R_j(t')\,dt' + 2\,H_{jspe}(x_{spe}) < L_j(age_{min},gender) \qquad (3)$$

where 20 combines the exposure over 20 trips and the factor 2 occurs since only 1 or 2 large solar particle events will occur in a given solar cycle (about 10.5 year duration). The dose rate in Eq. (3) is taken as the average value over the solar cycle. Unlike the singular missions where shield design is dominated by the possibility of solar particle events, the operation of the infrastructure will be dominated by the galactic cosmic ray exposures for which the limits in table 1 and 2 have large uncertainties. In this case, the shield requirements are tentative and may be quite different when the design uncertainty is reduced. We will consider two classes of missions separately as if crews are assigned to specific mission classes.

Lunar Transportation Infrastructure

The lunar mission profile will be taken as a 6-day transit to an L1 with a 5-day layover followed by a 2.5-day trip to the lunar surface with four separate pieces of equipment to support different mission segments. The surface stay is for 3-days followed by a 2.5-day return to L1 with a second 5-day layover and 6-day return to LEO. The crews consist of four men and women beginning their careers at age 45 and beginning in 2010 and continuing to 2020.



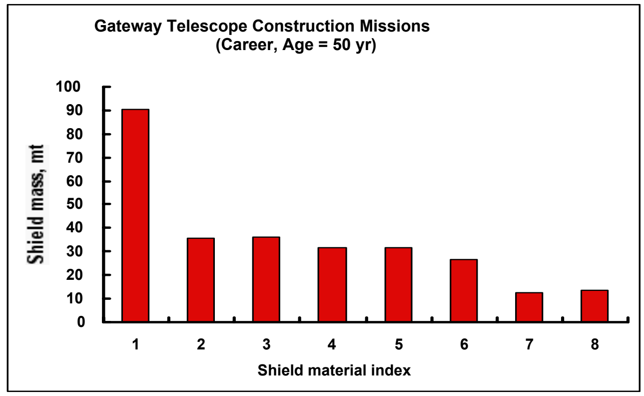


Fig. 7. Gateway nnfrastructure operations shield mass requirements for various materials.

Fig. 8. Gateway telescope construction career shied mass requirements for various materials

The dose rate exposure constraints remain the same but the career limits are given by Eq. (3). The resulting shield mass for this 45-year-old crew is shown in Figure 7. It is clear in this case that the present aluminum alloy base technology will be inadequate and development of advanced materials concepts will be enabling technology for the operation of such infrastructure. This will even be truer when reliability based design methods are implemented.

L1 Transportation Infrastructure

There are several possible missions to L1 for not only space science and tourism but as a possible gateway to deep space exploration to Mars and beyond. A reference profile for a single L1 mission is for 6 days in transit from and back to LEO with a 25-day mission stay as given in table 13 for aluminum alloy based technology. The crew size is taken as four members with careers beginning at age 35. The optimized profile for a single lifetime mission in 2014 using aluminum 2219 alloy is shown in table 13. The total shield mass in this case is 27.3 metric tons. There is a strong age dependence and increasing the age to 40 years eliminates the need for shielding in the wall beyond the minimum 1 g/cm2 and the shelter shield to only 28.7 g/cm2 resulting in only 7.4 metric tons of shield requirements for a single lifetime mission.

As can be seen, there is a great difference in requirements on age in addition to great differences in operation the infrastructure over the astronaut career as was seen in the lunar scenario. If the astronaut crew spends their careers operating beginning at age 50 years the L1 infrastructure shield requirements are shown in Figure 8. It is clear from the shield masses in Figure 8 that aluminum alloys stand our as poor candidate materials and the development of new materials will have an important impact on the operation of the Gateway infrastructure.

CONCLUSION

Even the present limited study of developing 100-day mission capabilities outside the Earth's protective magnetic field brings a host of issues revealed but not fully resolved in arriving at affordable solutions to further explore and develop space. This study is being extended to include the reliability based methods to deal with the great biological uncertainties. We do show that the once in a lifetime mission as was committed by NASA in the late 1960's and early 1970's are still possible under our current state of knowledge. The extension to operating a complex infrastructure with career astronauts immediately encounters massive shielding characteristic of a Mars mission scenario. The reason is simple, 20 few month missions add up to a long time for space exposure over the astronaut career. The next step is to develop reliability based design methods based on mainly the biological uncertainty of astronaut risks, which will impact on the current result.

REFERENCES

Badhwar G. D., Atwell W., Cash B., et al., Intercomparison of radiation measurements on STS-63, *Radiat. Meas.* **26 (6),** 147-158, 1997.

Badhwar, G. D. and O'Neill, P. M., Improved model of galactic cosmic radiation for space exploration mission, *Nucl. Tracks & Radiat.,* **20,** 403-410, 1992

National Council on Radiation Protection &Measurements, Radiation Protection Guidance for Activities in Low Earth Orbit. *NCRP Report* **132**, 2001.

National Council on Radiation Protection &Measurements, *Guidance on Radiation Received in Space.* NCRP Report **98,** 1989.

Tripathi R. K., Wilson, J. W., Cucinotta, F. A., Nealy, J. E., Clowdsley M. S., and Kim M. Y., Deep space mission radiation shielding optimization, *2001 International Conference on Environmental Systems,* July 9-12, Orlando, FL, **SAE,** 01ICES2326, 2001

Wilson, J.W., Shinn, J.L, Tripathi et al., Issues in deep space radiation protection. *Acta Astronautica.* **49(3)** 289-312, 2001.

Wilson, J.W., Kim M-H, Shinn, J.L., Tai, H., Cucinotta, F.A., Badhwar, G.D., Badavi, F.F., Atwell, and W.: Solar Cycle Variation and Application to the Space Radiation Environment**, NASA/TP-1999**-209369, 1999

Woolford, B., Connolly J. H., Campbell, P., Chapter 12: Human factors implications for shielding in Shielding *Strategies for Human Space Exploration.* **NASA CP** 3360, 1997.