Technology

Radiation Effects and Shielding Requirements in Human Missions to the Moon and Mars

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Abstract

Background: Radiation in space poses a threat to humans embarked on missions to the Moon or Mars. Several studies deal with allowable doses, levels of radiation doses in space, and effects of various forms of shielding. The recent shift in emphasis from "point estimates" to 95% confidence intervals adds significantly to the challenge in designing human space missions. Recent reports issued by NASA as well as the Exploration Systems Architecture Study (ESAS) have estimated radiation effects for some mission scenarios. Nevertheless, radiation effects and the effectiveness of shielding remain uncertain.

Method: Models and data in the literature are reviewed, and comparisons are made between allowable dose and estimated dose for lunar and Mars missions. Appraisals are made of the feasibility of providing radiation protection for crews in human missions to the Moon and Mars. A number of investigators have prepared point estimates of the doses due to galactic cosmic radiation (GCR) or solar particle events (SPE) for specific locations in space. However, the current NASA trend is to utilize the 95th percentile confidence interval (CI) rather than the point estimate for dose. In cases where the 95% CI has been modeled, the 95% CI dose is typically 3 to 4 times the point estimate. We have therefore multiplied point estimates by ~3.5 to roughly approximate 95% CI estimates, and compared them with allowable doses for various cases: (a) in space, (b) in space behind shields, (c) on the lunar surface behind various shields or within habitats, and (d) on the surface of Mars behind shields or within habitats.

Conclusion: For lunar sortie missions, the duration is short enough that GCR creates no serious risks. For lunar outpost missions the probability of encountering an SPE during Solar Maximum in a 6-month rotation is 1% to 10% depending on the assumed energy of the SPE. Even with > 30 g/cm^2 of regolith shielding the 95% CI dose from a major SPE would exceed the 30-day limit. The GCR during Solar Minimum for a 6-month stay on the Moon is marginal against the annual limit, but this can be mitigated somewhat by use of regolith for shielding the habitat.

For Mars missions, we conjecture a 400-day round trip transit to and from Mars, and about 560 days on the surface. The GCR 95% CI GCR dose equivalent with 15 g/cm^2 of aluminum shielding during Solar Minimum is about double the allowable annual dose for each leg of the trip to and from Mars. If a major SPE occurred during a transit, the crew would receive a sufficient dose to reduce their life expectancy by more than the 3% limit. The probabilities of encountering a large SPE are ~2.4% for a 4X 1972 SPE and about 20% for a 1X 1972 SPE in a round trip of 400 days during Solar Maximum.

On the surface of Mars, the accumulated GCR 95% CI dose over the course of a year is about 77 cSv, which exceeds the annual allowable of 50 cSv. For a 560-day stay on Mars, the cumulative 95% CI dose is about 120 cSv. This would exceed the career allowable dose for most females and younger males. The 95% CI dose from a major SPE would exceed the 30-day allowable dose. The probabilities of encountering a large SPE are ~3.4% for a 4X 1972 SPE and ~28% for a 1X 1972 SPE for 560 days on the surface during Solar Maximum.

Introduction

Allowable Dose

Because the biological effects of exposure to space radiation are complex, variable from individual to individual, and may take years to show their full impact, definition of allowable exposure will always include some subjectivity. Aside from the difficulty in quantifying the biological impacts of exposure to radiation in space, there is also subjectivity in defining how much risk is appropriate.

There are no guidelines for allowable radiation exposure in deep space. A common assumption is to use LEO guidelines as a first approximation for deep space. The standards presently adopted by the National Council on Radiation Protection and Measurement (NCRP) for low Earth orbit (LEO) are based on the "point estimate" for the levels of radiation that would cause an excess risk of 3% for fatal cancer due to this exposure. (It should be noted that if the mortality rate is 3% then the morbidity rate is probably closer to 4.5%.) These guidelines are summarized in Tables 1 and 2. It is conventional for most analysts to generate point estimates of radiation dose for various scenarios and then compare these with the allowable exposures in Tables 1 and 2. However, Cucinotta et al. (2005) have analyzed the uncertainty in predictions of risk of exposure-induced death (REID) and they have shown that error bars in the point estimates are large. The uncertainty in biological effects of space radiation were highlighted by a recent study that found significant differences between effects of protons and x-rays on DNA (Hada and Sutherland 2006). Cucinotta et al. (2005) adopted the 95% confidence interval (CI) as a basis for evaluating radiation risk, and this leads to risks that are typically a factor of 3 (or more) higher than those based on the point estimates. Therefore, when various investigators calculate point estimates of dose equivalent, these should be multiplied by a factor of ~3.5 to obtain a rough approximation to the 95% CI dose equivalent.

In some papers treating radiation effects, the allowable doses are treated as rigid requirements and shielding is sought to meet this requirement. This can lead to extreme conclusions in cases where the effects of shielding are minimal. For example, after GCR has passed though the Mars atmosphere, the low-energy components of GCR are removed, and application of further shielding on the Martian surface provides diminishing returns. Adding shielding in this case is an effort in futility. That is why Tripathi et al. (2001) reached the conclusion that:

> *"It is not practical to optimize for this mission with Al shielding material since exposure limitations require the aluminum shield to be in excess of 100 g/cm². These values of shield and shelter thickness are the maximum allowable values allowed in the optimization procedure."*

Instead, a more flexible procedure is suggested in which the estimated doses are compared with the admittedly uncertain

Table 1. Recommended organ dose equivalent limits for all ages from NCRP-98 (1989) and repeated by NCRP-132 (2001). "BFO" = blood-forming organs.

Exposure Interval	BFO Dose Equivalent (cSv)	Ocular Lens Dose Equivalent (cSv)	Skin Dose Equivalent (cSv)
30-day	25	100	150
Annual	50	200	300
Career	See Table 2	400	600

Table 2. LEO career whole body effective dose limits (Sv) from NCRP-132 (2001).

Age	25	35	45	55
Male	0.7	1.0	1.5	2.9
Female	0.4	0.6	0.9	1.6

suggested allowable doses, and the degree of risk is discussed in each case as a function of shielding proposed.

Radiation Sources

From the standpoint of radiation protection for humans in interplanetary space, the two important sources of radiation for lunar and Mars missions are:

- Heavy ions (atomic nuclei with all electrons removed) of the galactic cosmic rays (GCR).
- Sporadic production of energetic protons from large solar particle events (SPE).

Galactic cosmic radiation consists of the nuclei of the chemical elements that have been accelerated to extremely high energies outside the solar system. Protons account for nearly 91% of the total flux, alpha particles account for approximately 8%, and the, HZE (high charge and energy for $Z > 3$) particles account for less than 1% of the total flux. Even though the number of HZE particles is relatively small, they contribute a large fraction of the total dose equivalent.

At Solar Maximum conditions, GCR fluxes are substantially reduced producing a dose of roughly half of that produced by the Solar Minimum GCR flux.

The constant bombardment of high-energy GCR particles delivers a lower steady dose rate compared with large solar proton events that can deliver a very high dose in a short period of time (on the order of hours to days). The GCR contribution to dose becomes more significant as the mission duration increases. For the long duration missions, the GCR dose can become career limiting. In addition, the biological effects of the GCR high-energy and high-charge particles are not well understood and lead to uncertainties in the biological risk estimates. The amount of shielding required to protect the astronauts will depend on the time and duration of the mission.

Solar particle events (SPEs) occur when a large number of energetic particles, primarily protons with energies from a few MeV to few hundred MeV, move through the solar

system. These events happen during periods of increased solar activity. The larger and more dangerous solar particle events (SPEs) generally correspond to large coronal mass ejections (there are SPEs associated with isolated SPEs, but they are smaller and more localized than those generated in the shock ahead of large, fast CMEs. Most of the accelerated particles are protons, with a few percent helium and less than one percent higher Z elements, reasonably matching coronal composition. Large SPEs are extremely rare and last only a matter of hours. In the last fifty years, we have had only one or two per eleven-year solar cycle.

The largest SPEs observed in the past were the February 1956, November 1960, August 1972 and the October 1989 events. The largest SPEs recorded since August 1972 occurred in the months of August through October 1989. The magnitude of the October 1989 SPE was on the same order as the widely studied August 1972 event. The addition of the three 1989 SPEs, which occurred within 3 months of each other, can provide a fairly realistic estimate of the SPE environment that may be encountered during missions taking place in the 3 or 4 years of active Sun conditions (Solar Maximum). There are also smaller, more frequently occurring solar particle events, throughout a solar cycle. These events are not considered here since the shielding designed to reduce the GCR dose and a large solar particle event dose to within acceptable limits will dominate the shield design calculations.

The forecasting of large SPEs, such as the 1989 SPEs, will be of vital importance to warn crew-members of potentially lethal doses. Practically continuous monitoring of various aspects of solar activity (x-ray, and radio emissions, sunspot number, etc.) during Solar Cycle XXI (1975–1986) to the present time has provided a valuable database for SPE forecasting statistics. During recent years NOAA has examined the intensities of x-ray and radio emissions from the Sun and related them to the likelihood and severity of a subsequent energetic particle release. For 24-hr predictions during Solar Cycle XXI, the number of events that occurred without prediction of occurrence was about 10% of the total number predicted. This resulted primarily because the initial x-ray and radio bursts were not on the visible portion of the Sun. The false alarm rate was approximately 50%; that is, for every two SPEs predicted 24 hours in advance, one SPE actually, occurred. Large solar particle events are preceded by strong x-ray bursts that may be detected a minimum of approximately 20 minutes before the arrival of energetic particles at 1 AU. Thus, the likelihood of a proton event is more accurately predicted with a 20-minute warning time although the severity of the SPE is still not predicted with much success. Therefore, it becomes important to consider the case where a crew may only have a 20-minute advance warning that energetic protons may arrive. The October, 1989 SPE was predicted successfully by NOAA from an x-ray burst that occurred approximately 1 hour before SPE onset. The impact of a potentially large solar proton event during surface activities away from the base is an operational concern that mission planners must address (Simonsen et al.

1997).

The foregoing discussion may be summarized as follows:

SPEs have the following characteristics:

- Occur sporadically near Solar Maximum.

- Appear to correspond to large coronal mass ejections - mainly protons.

- Large SPEs are extremely rare and last only a matter of hours or days.

- In the last 50 years, we have had only 1 or 2 large SPEs per 11-yr solar cycle.

- Largest SPEs observed in the past are the February 1956, November 1960, August 1972 and October, 2003 events.

- Likely 20-minute warning time for onset.

GCRs have the following characteristics:

- GCRs consist of the nuclei of the chemical elements that have been accelerated to extremely high energies outside the solar system.

- Protons account for nearly 91% of the total GCR flux, alpha particles account for approximately 8%, and HZE (high charge and energy for Z > 3) particles account for < 1% of the total flux.

- Even though the number of HZE particles is relatively small, they contribute a large fraction of the total dose equivalent.

- At Solar Maximum conditions, GCR fluxes are substantially reduced producing a dose of roughly half of that produced by the Solar Minimum GCR flux.

A comparison of GCR and SPE is as follows:

- The constant bombardment of high-energy GCR particles delivers a lower steady dose rate compared with large SPEs that can deliver a very high dose in a short period of time (on the order of hours to days).

- The GCR contribution to dose becomes more significant as the mission duration increases.

- For long duration missions, the GCR dose can become career-limiting or annual-limiting.

- The biological effects of the GCR high-energy and high-charge particles are not well understood and lead to uncertainties in the biological risk estimates.

- The main threat of SPEs is against the 30-day exposure limit.

- SPE energies are far lower than GCR and are more amenable to mitigation by shielding.

- The amount of shielding required to protect the astronauts will depend on the time and duration of the mission.

The effect of shielding is complex:

Cohen (2004) provides an excellent discussion of alternative materials for shielding with their pros and cons. He

emphasizes both the transmissivity of shields as well as production of secondaries, that "can cause more biological damage than the primaries that triggered them." he shows that the lighter elements (H through C) emit far fewer secondaries than aluminum.

It turns out that Aluminum, regolith and CO_2 all have roughly the same shielding effect per g/cm².

- The Mars atmosphere is equivalent to ~ 16 g/cm².
- An aluminum wall is about 2.7 g/cm² per cm of thickness.
- Lighter materials with high hydrogen content are more effective per g/cm².
- Each interaction of energetic radiation with matter yields secondaries.
- Tracing the pathways of radiation and secondaries through habitat walls and human targets is a complex problem.

Radiation Fluences

The natural radiation environment encountered during a lunar or Mars mission will vary depending on the solar activity (measured by sunspot number). The solar dipole moment cycles approximately every 20-24 years leading to solar activity cycles of 10-12 years modulated by the direction of the dipole moment. The solar activity increases with the decline of the dipole moment with maximum activity occurring as the dipole switches hemispheres. Activity declines as the dipole moment maximizes along its new direction. With each activity cycle, there are approximately 3.5 to 4 years of active solar conditions. The greatest probability of a large solar proton event occurs during this rise and decline in solar activity. The magnitude of the GCR flux varies over the 10-12 year solar cycle. The fluxes are greatest during Solar Minimum conditions when the interplanetary magnetic field is the weakest, allowing more intergalactic charged particles to gain access to our solar system. During maximum solar activity, the GCR fluxes are at their minimum, however, the probability of a large solar proton event increases significantly. For most analyses, a conservative radiation environment is selected for estimating shield requirements. Typically, a SPE environment can be assumed that consists of a single large SPE occurring during the mission. The GCR environment at Solar Minimum conditions is almost always selected for conservatism. However, one should not consider a SPE in combination with GCR at Solar Minimum because solar SPE mainly occur near Solar Maximum.

The models used by various investigators are generally similar. It is assumed that during the progress of a mission there is a steady input of GCR radiation and in the worst case, one major SPE that might occur within any of the mission legs. Tripathy et al. (2001) provide estimates of the GCR fluence at Solar Maximum and Solar Minimum in free space as well as on the Martian surface. On Mars, the presence of the Martian atmosphere attenuates the incident ions and produces additional ionic fragments and more energetic neutrons are produced in the atmosphere overhead.

Simonsen (1997) and Tripathi et al. (2001) provide comparisons of fluences for three major SPEs. These figures show that the effect of the Mars atmosphere on GCRs is relatively minor, whereas the attenuation of SPEs is significant.

In order to be useful for mission planning fluences need to be converted to dose equivalents.

Radiation Effects on Humans

Definitions and Units

Radiation in space before it interacts with matter is usually defined by particle fluxes in various energy bands.

The energy actually absorbed by a sample of a biological system is obviously of greatest importance. For this reason, the concept of absorbed dose is used, i.e., the energy absorbed per unit mass. An absorbed dose applies to the energy deposited by any kind of radiation in any kind of material. The unit of absorbed dose was originally defined as the rad, that is equivalent to the absorption of 100 ergs of energy per gram of material. This has since been replaced by the Gray (Gy) that is equal to 100 rads (1 Joule/kg).

In regard to the impact of high-energy radiation on humans, it is useful to define a quantity, the dose equivalent, which describes the effect of radiation on tissue. Equal absorbed doses of radiation may not always give rise to equal risks of a given biological effect, since the biological effectiveness may be affected by differences in the type of radiation or irradiation conditions. The dose equivalent was originally defined to be the product of the absorbed dose and a modifying factor or factors:

Dose Equivalent = Absorbed Dose (rads) × Quality (1)
Factor

where the quality factor, the most common modifying factor, takes into account the relative effectiveness of the radiation in producing a biological effect. The special unit of dose equivalent was the *rem*. The value of the quality factor for each type of radiation depends on the distribution of the absorbed energy in a mass of tissue. For example, the increased effectiveness of neutrons relative to gamma rays is related to the higher specific ionization of the recoil protons liberated by neutron bombardment as compared to the specific ionization of the secondary electrons arising from gamma ray irradiation. The values of quality factors are known to vary with the biological effect being observed, and are still a matter of controversy for the same biological effect.

In current work, the unit of dose equivalent is the *Sievert* (Sv) and the quality factors are replaced by radiation *weighting factors (WR)* with the *absorbed dose* in Gy. Thus:

Dose Equivalent (Sv) = *Absorbed dose* (Gy) × *WR*   (2)

One Sv is equivalent to 100 rem.

All of the above units may have prefixes with c = 1/100 and m = 1/1000 so that (for example) 1 cSv = 0.01 Sv.

The equivalent and absorbed doses discussed above refer to specific organs. In addition, an *effective dose* is defined for the whole body as the sum of weighted dose equivalents in all the organs and tissues of the body.

Effective dose (whole body) = sum of (*organ doses × tissue weighting factors*). Tissue weighting factors represent relative sensitivity of organs for developing cancer.

A summary of definitions and units is provided in Table 3.

Table 3. Summary of Definitions and Units.

Phenomena	Units
Fluence of particles in space	Number of particles per cm² per MeV/AMU per year
Absorbed dose	gray = absorption of 1 J of energy per kg of material
Dose Equivalent	Sievert = grays x weighting factors
Effective dose	Sieverts

Radiation Effects on Humans

Most of the data and understanding of radiation effects relates to x-ray and gamma-ray exposure, and relatively little is known about continuous low dose rate heavy-ion radiation. Recently, Hada and Sutherland (2006) investigated the levels and kinds of multiple damages, called damage clusters, produced by high-energy radiation beams. They used beams of high-energy charged particles (protons, as well as iron, carbon, titanium, and silicon ions) and exposed DNA in solution to each type of radiation. They then measured the levels of three kinds of damage clusters, as well as double-strand breaks produced as a result of the exposure. Damage clusters are dangerous because they can cause genetic mutations and cancers, or they can be converted to double-strand breaks. They found that protons produced a spectrum of cellular damage very similar to the pattern caused by high-energy iron ions and other heavy charged particles. These results cast doubt on the extrapolation of radiation effects from x-ray and gamma-ray exposure to energetic proton exposure.

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.

Clowdsley et al. (2005) point out that conventional dose limits have a large biological uncertainty associated with them, and that new exposure limits for lunar missions may require a 95% confidence interval of remaining below the

3% excess fatal cancer probability. It is claimed that preliminary studies show that this may decrease allowable astronaut exposure time by up to a factor of 6. The essential factor here is that in estimating the biological impact of a given level of radiation, one estimates a point dose (analogous to a point design) that includes uncertainty. If the uncertainty is large, the requirement of 95% confidence can increase the estimated exposure by a significant factor compared to the point dose. However, Cucinotta et al. (2005) indicate that the increase is more like a factor of 3 to 4 than 6.

Radiation exposure limits have not yet been defined for missions beyond low Earth orbit (LEO). For LEO operations, in addition to a federally mandated obligation to follow the ALARA principle of keeping exposure as low as reasonably achievable, NASA adopted and OSHA has approved the radiation exposure recommendations of the National Council on Radiation Protection and Measurements (NCRP) contained in NCRP Report No. 98 (1989). This report contains monthly, annual, and career exposure limits in dose equivalents. The career limits were based on dose equivalents to blood-forming organs, and not on effective dose to the entire body. About 12 years later, the NCRP recommended new exposure limits contained in NCRP Report No. 132 (2001). These limits are based on "point estimates."

For high-energy radiation from GCR and SPEs, the dose delivered to the vital organs is the most important with regard to latent carcinogenic effects. This dose is often taken as the whole-body exposure and is assumed equal to the blood-forming organ (BFO) dose. When detailed body geometry is not considered, the BFO dose is conservatively computed as the dose incurred at a 5-cm depth in tissue (can be simulated by water). A more conservative estimate for the skin and eye dose is made using a 0-cm depth dose. Dose-equivalent limits are established for the short-term (30-day) exposures, annual exposures, and career exposure for astronauts in low-Earth orbit. Short-term exposures are important when considering SPEs because of their high dose rate. Doses received from GCR on long-duration missions are especially important to annual limits and total career limits. Long-term career limits determined by the age and gender of the individual.

Current thinking (Anderson et al. 2005) seems to favor use of the LEO limits as guidelines for deep space mission exposures, principally because computation of conventional exposures based on linear energy transfer (LET) in a target medium by flux of ionizing radiation may be performed with little ambiguity. However, the basis for radiation damage to mammalian cellular systems by continuous low dose rate heavy-ion radiation (galactic cosmic rays - GCR) is related to LET in an indirect and complex fashion. For a given ionizing particle species and energy, cell damage are highly variable for different cell types.

Reitz and Sandler (1995) provide further insight into the

setting of these standards: "Although space flight is considered by most experts as a risky occupation, the [ICRP] committee found a lifetime excess risk for fatal cancer due to radiation exposure of 3% reasonable, taking into account the fact that space crews have other serious risks besides radiation risk. This risk of 3% is comparable with the risk in less safe but ordinary industries, such as agriculture and construction, and it is lower than that for the more highly exposed radiation worker on the ground, corresponding to a lifetime risk of 5%.... Still, as a larger segment of the population is asked to participate, this 3% level may be found to be unacceptable.... A more acceptable fatality risk level may be that of 1% of the working lifetime that occurs with automobile travel in the U.S. and radiation workers generally."

Furthermore, if the risk of death from cancer is 3%, the risk of contracting cancer must be higher because not all cancer cases are fatal. Cucinotta et al. (2005) estimate that the risk of contracting cancer is about 4.5% if the risk of death from cancer is 3%.

An interesting study was reported by Cohen (2004) in which the biological impact of 1 GeV iron particles was measured by counting chromosomal aberrations (dicentrics, translocations, complex-type exchanges, rings, acentric fragments) in lymphocyte cell samples ranging from 150 to 3000 cells per dose. He found that in comparing polyethylene shields with carbon shields, the polyethylene produced a lower dose but a greater biological effect than carbon.

Computation of Effective Doses

Computation Procedure

In general, the following steps need to be taken:

1) Break down a mission into legs, each with its own duration. For example, Mars missions may involve mainly transit to Mars (~180 days), surface stay (~600 days) and return from Mars (~180 days).

2) For each leg of the mission, define the appropriate extraterrestrial energetic particle fluences due to GCR and SPE.

3) Where there is an atmosphere, such as on the surface of Mars, calculate the effect of the atmosphere and thereby estimate the energetic particle fluences that arrive at the surface.

4) Estimate the energetic particle fluence inside a habitat. A cruder approximation is to simply model the fluence emanating from a sheet of material, typically aluminum.

5) Convert this net fluence into absorbed, equivalent and effective doses. If only point estimates are made, roughly estimate the 95% confidence intervals by multiplying the effective dose by about 3.5.

6) Compare these estimated doses with allowable doses.

However, none of the papers and reports in the literature provided sufficient detailed data and descriptions to allow the reader to track the progress in detail all the way through this sequence.

Doses in Free Space

Tripathy et al. (2001) provide estimates of the annual GCR dose equivalent to ocular lens as a function of time over many solar cycles. The annual GCR dose equivalent tends to peak around 1 Sv at Solar Minimum and bottoms out around 0.5 Sv at Solar Maximum. The annual dose equivalent for blood forming organs (BFO) was estimated to peak around 0.7 Sv at Solar Minimum and bottom out around 0.35 Sv at Solar Maximum. Simonsen et al. (1997) estimated the annual 5-cm GCR dose at Solar Minimum to be 0.58 Sv.

Clowdsley et al. (2004) provide the following estimates:

- Effective dose for male astronauts exposed to the free space 1977 Solar Minimum GCR environment = 0.62 Sv/year.

- For Solar Maximum this estimate drops to 0.23 Sv/year.

Rais-Rohani (2005) indicates that the GCR BFO dose equivalent at Solar Minimum is 60 rem per year.

It should be noted that the 95% CI GCR dose in free space (about 3.5 times the point estimate) will reach the allowable annual BFO dose limit of 50 cSv (see Table 1), in about 3 months.

The dose in free space due to a major SPE can be very large (perhaps up to about 100 Sv). However, even a very small amount of physical shield will greatly reduce the dose behind the shield, and therefore it is not very useful to discuss the dose in free space.

Radiation Shielding Materials

The effectiveness of any shield material is characterized by the transport of energetic particles within the shield, which is 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. 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 (Cohen 2004). However, organic polymers may be useful. 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 such as polyethylene show enhanced protection properties. 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. Graphite nano-fiber materials heavily impregnated with hydrogen may be considered in futuristic space structures.

Tripathi et al. (2001) incorporated the results of detailed transport calculations for various shielding materials into a shield design database. The chemical composition and mass density are the most important factors in determining the effectiveness of a shield material. These data were then used to estimate doses behind these shields. Clowdsley et al. (2005) and Clowdsley et al. (2004) calculated doses behind various shields.

Simonsen (1997) discusses shielding materials in some depth. Aluminum and lunar regolith were selected for study because they can provide a convenient shield material on the lunar surface. Materials having high hydrogen content were also selected because such substances are known to be most effective for high-energy charged particle shielding on a per-unit-mass basis. Furthermore, when any material used as a radiation shield can serve a dual purpose, mission costs can usually be reduced. Other examples of "dual use" materials are foodstuffs, water, and waste-water. Lithium hydride and borated polymers were considered for space applications because of their usage in nuclear reactor facilities for neutron moderation and absorption. However, shielding the crew from reactor radiation presents its own challenges. The addition of various weight percent loadings of boron to polyethylene and polyetherimide was considered because of the large thermal neutron cross section of boron-10. Polyetherimide was selected because it is a space-qualified, advanced, high performance polymer. As opposed to polyethylene, polyetherimide can be used as the matrix resin for composite materials allowing for structural applications. Finally, regolith-epoxy mixtures were considered as a means to increase the shielding and structural properties of in-situ resources. The propagation results were evaluated as dose (or dose equivalent) versus areal density (in units of g/cm^2) that can be converted to a linear thickness (cm) by dividing by the density (g/cm^3) of the appropriate material.

Doses Behind Shields in Space

Simonsen et al. (1997) estimated the GCR dose equivalent in space behind shields made from various materials at Solar Minimum conditions. A comparison of the shielding effectiveness of the various materials is shown in Figure 1 for the 5-cm depth dose (the dose expected after passing through 5 cm of water located behind the shield).

Aluminum and regolith behave similarly in their general attenuation characteristics with the regolith having slightly better shielding properties. Polyethylene and lithium hydride are also very similar in nature, and water and magnesium hydride are comparable materials of intermediate shield effectiveness in relation to the others. The better shielding characteristics for the materials containing hydrogen are also apparent, particularly in the case of polyethylene and lithium hydride. It is noteworthy that moderate amounts of shielding reduce the dose from GCR due to removal of lower energy

components, but the effectiveness of shielding approaches diminishing returns beyond about 20 g/cm^2 due to penetration of higher energy components of GCR.
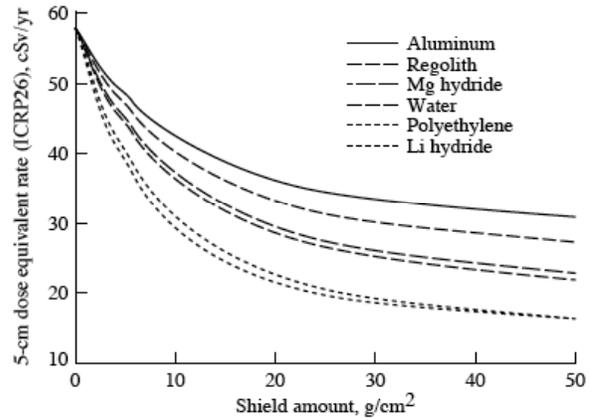
Figure 1. Point estimates of 5-cm depth dose for GCR at Solar Minimum as a function of areal density for various materials (figure1.jpg). (Simonsen et al. 1997)
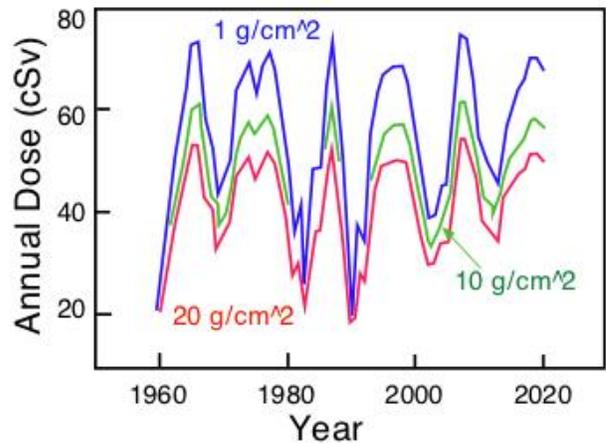
Figure 2. Point estimates of GCR annual dose equivalent to blood-forming organs within an Al-2219 shielded region (figure2.jpg). (Tripathi et al. 2001)

Tripathi et al. (2001) provide Figure 2 that shows the shielding effect of various thicknesses of aluminum for GCR.

Clowdsley et al. (2004) estimated the doses inside a sphere in the space environment not far from Earth made of a material of variable thickness. Figure 3 shows their point estimates for the effective GCR dose rates in free space as a function of the thickness of shield. With a minimal shield of 2.5 g/cm2, the estimated dose is about 0.165 cSv/day. The likely 95% CI dose would be about 0.58 cSv/day. This would imply that the 30-day limit is not exceeded but the annual limit of 50 cSv (Table 1) would be exceeded in about 3 months. Figure 4 shows the point estimate of the dose due to a presumed SPE with intensity equal to 4 times the September 1989 SPE. The dose is about 80 cSv behind 5 g/cm2 of Al and this
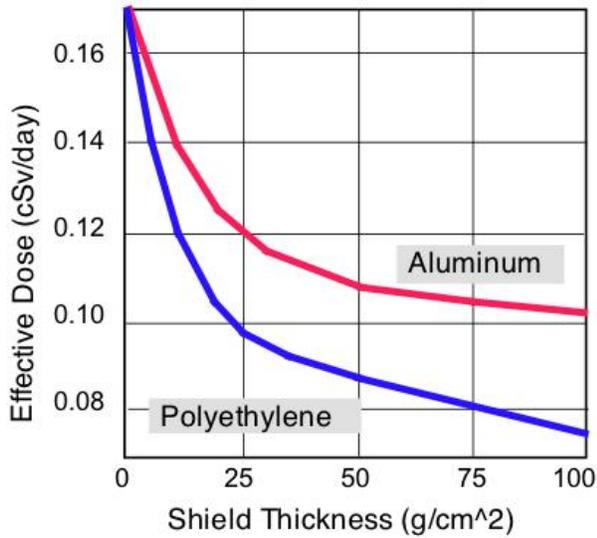
Figure 3. Point estimates of effective dose for male astronauts behind polyethylene or aluminum spherical shielding exposed to the free space 1977 Solar Minimum GCR environment (figure3.jpg). (Clowdsley et al. 2004)
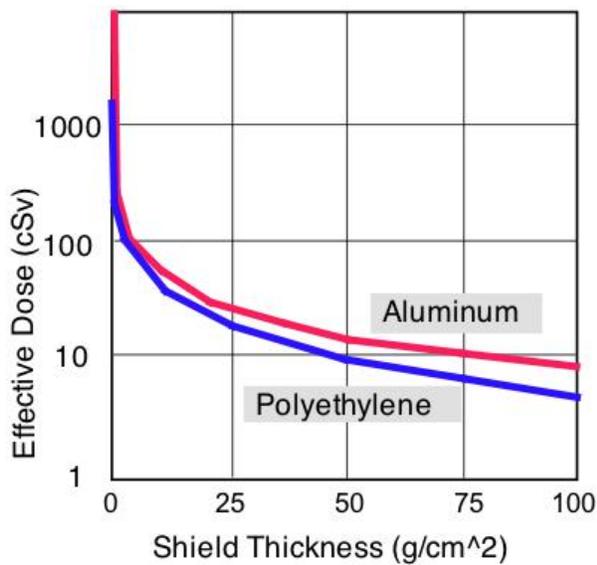
Figure 4. Point estimates of effective dose for male astronauts behind polyethylene or aluminum spherical shielding exposed to 4 times the September 1989 SPE (figure4.jpg). (Clowdsley et al. 2004)

greatly exceeds the allowable 30-day limit.

Cucinotta et al. (2005) provided the point estimate data shown in Figure 5. According to this reference, no shielding is very effective against GCR although graphite is somewhat better than the others. Shielding is very effective against SPEs although rather heavy layers of shielding may be needed to reduce the dose equivalent down to the 30-day allowable. Solar protons are less penetrating than GCR and are effectively mitigated by shielding. For heavy shielding ($\geq$ 20 g/cm^2), GCR dominates over SPEs and further addition of
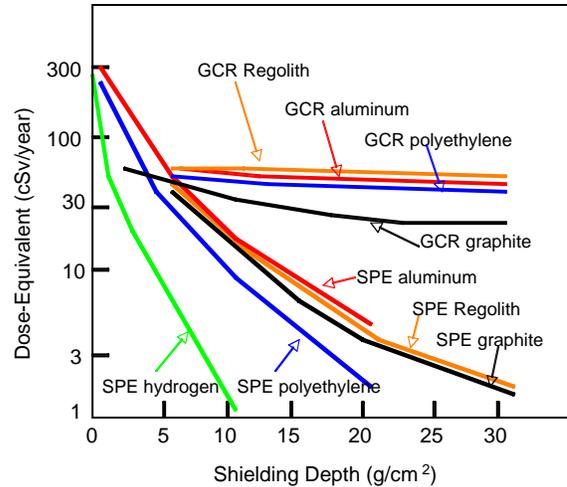
Figure 5. Effective dose (bottom panel) behind various shields for Solar Minimum GCR and August 1972 SPE (the units for the SPE doses are for total event and not necessarily per year) (figure5.jpg). (Cucinotta et al. 2005)

shielding provides marginal reductions. Each SPE is unique in that it has distinct fluence, energy spectra, and dose rates.

Dose on the Lunar Surface

Clowdsley et al. (2005) state: "An astronaut on the surface of the Moon is protected from the GCR environment in 2π directions by the lunar regolith. However, there are low energy neutrons and light ions produced as a result of interaction between the galactic cosmic rays and the lunar regolith that make a small contribution to astronaut dose. For these reasons, the radiation environment on the lunar surface is slightly more than half as intense as that of free space."

Using a space radiation transport code, Clowdsley et al. (2005) derived a point estimate that the maximum daily effective GCR dose for an astronaut in an EVA suit exposed on the lunar surface is 0.085 cSv (about half of what they calculate for free space). The 1977 Solar Minimum environment was used as a worst-case GCR environment and it was assumed that the EVA suits on the lunar surface provide no radiation protection.

Simonsen (1997) calculated the effective dose received on the Moon due to SPEs and GCR. This reference estimated the effect of using lunar regolith as shielding for a habitat on the Moon. These results are reproduced in Figures 6 and 7.

Dose on the Mars Surface

The first step is to estimate attenuation due to the Martian atmosphere, and then the effect of regolith shielding on the remainder that reaches the surface. Simonsen (1997) calculated the effective dose received on Mars due to SPEs and GCR as a function of the column density of the CO_2 gas in the Martian atmosphere measured in g/cm^2. A typical
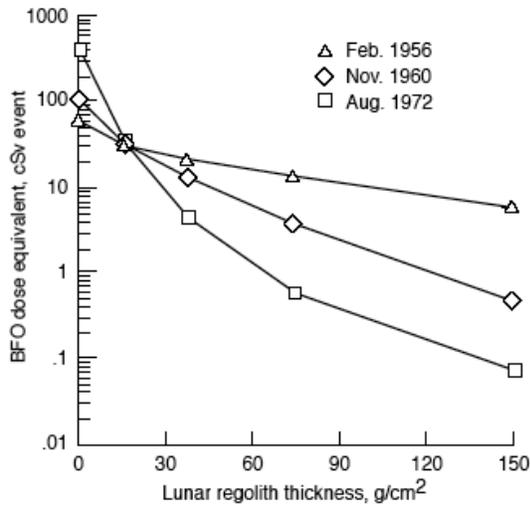
Figure 6. Point estimates of BFO dose equivalent as a function of lunar regolith thickness for three large SPEs (figure6.jpg). (Simonsen 1997)
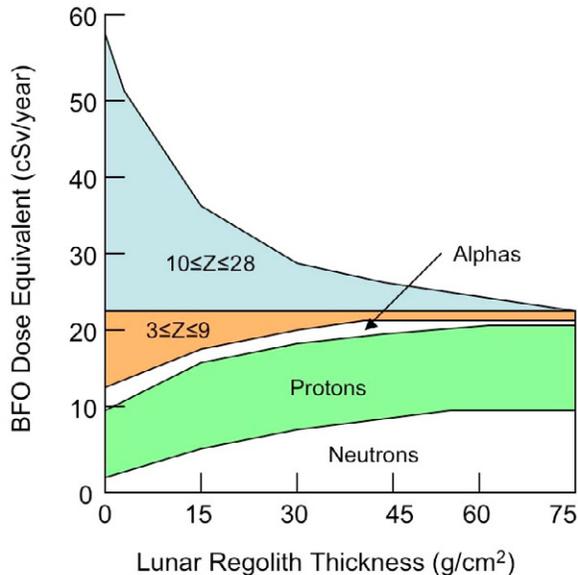
Figure 7. Point estimates of BFO annual dose-equivalent contributions from specified particle constituents as a function of lunar regolith thickness for GCR at Solar Minimum conditions (figure7.jpg). (Simonsen 1997)

Mars atmosphere is 16 g/cm^2 (Simonsen 1997, Cucinotta et al. 2005).

Simonsen (1997) found that the 16 g/cm^2 Mars atmosphere reduced the point estimate of the BFO dose equivalent from major SPEs from high values to about 30 to 35 cSv per event.

The effect of the same Mars atmosphere on GCR is as follows:

- At Solar Minimum the point estimate of dose equivalent is
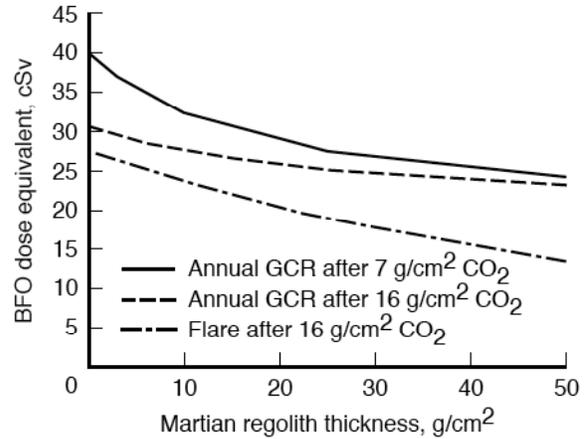
Figure 8. Point estimates of BFO dose equivalent as a function of regolith thickness after transport through the Martian atmosphere in the vertical direction (figure8.jpg). (Simonsen 1997)

reduced by the atmosphere from about 57 cSv/yr to about 32 cSv/yr at the surface.

- At Solar Maximum the point estimate of dose equivalent is reduced by the atmosphere from about 22 cSv/yr to about 15 cSv/yr at the surface.

When Mars regolith is considered as a protective shield medium, the transport calculations must be made for the combined atmosphere-regolith thicknesses. In this case, the detailed flux/energy spectra emergent from a specified carbon dioxide amount is used as input for the subsequent regolith calculation. Sample BFO dose results for such a procedure are given in Figure 8, where fixed carbon dioxide amounts are used in conjunction with increasing regolith layer thicknesses. Three sample transport calculations are shown here: two GCR cases and the energetic February 1956 SPE. Presumably, the SPE data are per event and the GCR data are per year (not specified by Simonsen (1997)).

These results show that after passing through the Martian atmosphere, the low energy components of space radiation are reduced, and regolith has relatively little effectiveness in shielding against the high-energy remainder.

Dose Within Habitats

When the computed propagation data for the GCR and SPE protons are applied to specific shield geometries, the dose at specified target points throughout a habitat can be evaluated. Examples using this methodology were presented by Simonsen (1997) for both lunar and Mars surface habitat modules.

Lunar Habitats. Lunar surface habitation dose calculations were based on point estimates on the lunar surface:

1) The dose (without shielding) from GCR is taken as 57 cSv per year.

2) The dose (without shielding) from a large SPE

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(February 1956) is taken as about 100 cSv.

Models indicate that a 50-cm thickness of regolith (75 g/cm^2 assuming a regolith density of 1.5 g/cm^3) will reduce the BFO dose-equivalent to approximately 25 cSv/yr for the GCR and 15 cSv for one large SPE (February 1956) (Simonsen 1997). With the 2π solid angle shielding provided by the lunar surface and the 50-cm regolith layer, the annual dose for this environment (GCR + 1 SPE) is reduced to approximately 20 cSv. Thus, a minimum shield thickness of 50-cm was selected for analysis to reduce point estimate BFO dose levels to slightly less than half of the annual limit of 50 cSv as given in Table 1. Shield thicknesses of 75 cm (112.5 g/cm^2) and 100 cm (150 g/cm^2) were also selected for analysis to estimate the extent to which additional shielding can further reduce incurred doses. However, this work was done prior to the recent trend that suggests that 95% confidence intervals will replace point estimates. In that case, the point estimates will increase by roughly a factor of 3.5 and 50-cm of regolith would be inadequate.

Simonsen (1997) utilized a lunar habitat concept based on a modified space station module. The module was assumed to be lengthwise on the lunar surface and covered with either 50 cm or 100 cm of lunar regolith overhead. Along the sides, the regolith material is filled in around the cylindrical module to form a vertical wall up to the central horizontal plane. For the 50-cm layer, the shield thickness will vary from 230 cm to 50 cm from ground level up to the top of the habitat. To evaluate the dose at particular points within the habitats, the radiation from all directions must be determined. In free space, radiation will surround the crew from the full 4π solid angle. However, on a planetary surface, only a solid angle of 2π is considered because the mass of the planet protects the crew from half of the free-space radiation. The dose contribution attributed to particles arriving from a given direction is determined by the shield thickness encountered along its straight-line path to specified target points. For the shield assessments, the regolith thicknesses and the corresponding dosimetric quantities were evaluated for zenith angles between 0° and 90° in 5° increments and for azimuth angles of 0° to 360° also in 5° increments. The regolith shield thickness distributions were calculated by Simonsen (1997) using geometric models.

The integrated BFO dose point estimates that would have been incurred from the three SPEs using shield thicknesses

Table 3. Point estimates of BFO dose comparison for three large SPEs for lunar habitats. (Simonsen 1997)

SPE Occurrence	Regolith Thickness (cm)	Estimated Dose in Cylinder (cSv)
February 1956	50	7.5
	100	2.7
November 1960	50	1.6
	100	0.2
August 1972	50	0.3
	100	<0.1

of either 50 cm or 100 cm are shown in Table 3.

These values represent the dose in the center of the habitat for each SPE. The dose distribution was also calculated throughout each habitat. The BFO dose variations within these habitats show little change for heights above and below the center plane.

Dose estimates within lunar habitats were calculated for the GCR at Solar Minimum conditions (Simonsen 1997). The maximum integrated BFO dose for a regolith shield thickness of 50 cm was estimated to be 12 cSv/yr and the dose variation throughout the configuration was relatively small. Using the dose estimates calculated within the habitat, surface mission doses can be estimated. A very conservative estimate of dose is to assume the crew receives the dose delivered from the GCR at Solar Minimum and the dose delivered from one large SPE (in this case, the February 1956 SPE since it delivers the largest dose in the shielded module). The surface habitat doses are shown in Table 4 for different stay times as specified by the mission scenario for the cylindrical habitat.

Table 4. Lunar Surface Mission Dose Point Estimates Inside Cylindrical Habitat Based on ISS Habitat. (Simonsen 1997)

Stay Time	GCR Dose (cSv)	February 1956 SPE Dose (cSv)	Mission Surface Dose (cSv)
30 days	1	7.5	8.5
6 months	6	7.5	13.5
1 year	12	7.5	19.5

All of the surface dose point estimates are well below the allowable levels from Table 1 but when adjusted to 95% CI values, they are marginal. The above estimates did not take into account the added shielding provided by the pressure vessel wall, supporting structures, or the placement of equipment in and around the module. The dose in-transit to the Moon and possible larger doses received during EVA's are not included. The SPE dose contribution dominates the shorter missions while the GCR contribution starts to dominate the longer missions. Shielding from SPE will be essential on the lunar surface whether in the form of heavily shielded areas (i.e., SPE shelters) or overall habitat protection for any mission duration. For longer stay times on the surface, the shielding from GCR becomes necessary to reduce the crew-members' annual exposures and overall career exposure. A regolith shield thickness on the order of 50 cm was estimated to provide adequate SPE and GCR protection based on point estimates of doses.

Mars Habitats. The amount of protection provided by the Mars atmosphere from free-space radiative fluxes must be evaluated prior to estimating the effect of additional shielding for crew-members while on the surface. The composition and structure of the atmosphere as well as the crew-members altitude will determine the extent of the

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atmospheric protection.

The surface doses at various altitudes in the atmosphere were determined by Simonsen (1997) from the computed propagation data for the GCR and SPE protons in carbon dioxide. The dosimetric values at a given target point were computed for carbon dioxide absorber amounts along slant paths in the atmosphere. In these calculations, a spherical concentric atmosphere was assumed such that the amount of protection provided increases with increasing zenith angle. For a given target point, the absorber amounts and the corresponding dosimetric quantities were evaluated for zenith angles between 0° and 90° in 5° increments. The dose equivalents corresponding to each absorber thickness at each zenith angle were log-linearly interpolated/extrapolated from the basic carbon dioxide dose vs. depth propagation data. The calculated directional dose was then numerically integrated over a 2π solid angle to obtain the total dose at the point of interest (the dose from the other 2π solid angle is assumed zero because of planetary shielding). Integrated total dose calculations were made for both the high- and low-density atmosphere models at altitudes of 0, 4, 8, and 12 km. Results for 0 km and 4 km are shown in Table 5.

Results in Table 5 include dose point estimates for the GCR at Solar Minimum and Maximum conditions and the SPE events of 1956, 1960, 1972, and 1989. The range in doses indicated in the table is a result of the different atmospheric models used. The incurred GCR dose during Solar Maximum conditions is approximately half of the dose incurred during Solar Minimum conditions. The GCR dose remains relatively constant with altitude compared with the range of estimated SPE doses.

The SPE doses were estimated using the fluence at 1 AU. In the vicinity of Mars (approximately 1.5 AU), the fluence of these SPEs is expected to be less. One estimate is that the radial dispersion of the SPE particle flux is inversely proportional to the square of the distance from the Sun. However, large variations in this behavior may be expected primarily due to inhomogeneities in the interplanetary magnetic field, anisotropic flux properties and the nature of the energy spectrum. There is still much discussion on the dependence of a SPE's radial dispersion with distance. It is left to the judgment of the reader as to whether the estimated SPE doses should be multiplied by $1/r^2$ (where r is the distance from the sun in astronomical units; $r \sim 1.5$ AU for Mars).

The values in Table 5 can be used to estimate the total incurred dose while on the surface of Mars during a variety of hypothetical missions occurring at various times during the solar cycle. In this regard, Simonsen (1997) states that the data in Table 5 are based on the assumption that the crew members' only protection is the carbon dioxide atmosphere; i.e., the pressure vessel and other supporting equipment are not included as shielding, but this approximation is only slightly conservative because moderate amounts of additional shielding will not provide substantial additional protection compared with that already provided by the atmosphere. Nevertheless, the results of Table 5 provide an optimistic view of the radiation protection properties of the Martian atmosphere.

Anderson et al. (2005) examined exposure and subsequent risk for humans in residence on Mars. A conceptual habitat structure, CAD-modeled with duly considered inherent shielding properties, was implemented. Body self-shielding was evaluated using NASA standard computerized male and female models. The background environment was taken to consist not only of exposure from incident cosmic ray ions and their secondaries, but also included the contribution from secondary neutron fields produced in the tenuous atmosphere and the underlying regolith.

Quoting from Anderson et al. (2005):

"The planet Mars is accessible at the present time, and implementation of a short-duration mission only needs sufficient public support and provision of necessary resources. The journey to Mars is projected to take ~ ½ year, and an initial visit may be a short-stay (or "sprint") mission. In the present study, we address the case of a semi-permanent habitat, or outpost, set in place to accommodate a long-duration stay (~1½ to 2 years). Many technical problems must be addressed in the case of the short-duration mission, but additional challenges arise for the long-stay mission, not the least of which is the problem of space radiation exposure."

It is fortunate that this paper restricts its modeling to long-stay Mars missions, which, though extremely challenging, are far more credible than short-stay missions.

The landed habitat and science laboratory was modeled for a crew of four. It was designed to provide crew accommodations and lab support for surface missions, along

Table 5. Point estimates of integrated BFO Dose (cSv) on the surface of Mars at two elevations. (Simonsen 1997)

Radiation Source	BFO Dose at 0 km elevation	BFO Dose at 4 km elevation
GCR at Solar Minimum (annual)	10.5 – 11.9	12.0 – 13.8
GCR at Solar Maximum (annual)	5.7 – 6.1	6.2 – 6.8
Feb. 1956 SPE	8.5 – 9.9	10.0 – 11.8
Nov. 1960 SPE	5.0 – 7.3	7.5 – 10.8
Aug. 1972 SPE	2.2 – 4.6	4.8 – 9.9
Aug. 1989 SPE	0.1 – 0.3	0.3 – 0.6
Sept. 1989 SPE	1.0 – 2.0	2.0 – 3.8
Oct. 1989 SPE	1.2 – 2.7	2.8 – 5.9

Table 6. Point estimates of GCR annual dose equivalent within habitat vs. water shielding (g/cm^2) for a fixed Mars atmosphere of 16 g/cm^2 (Anderson et al. 2005).

Water shielding (g/cm^2)	Annual Dose Equivalent (cSv)
0.3	78
2.0	69
5.0	63
10.0	54
15.0	49
20.0	46
30.0	43
50.0	39
100.0	33
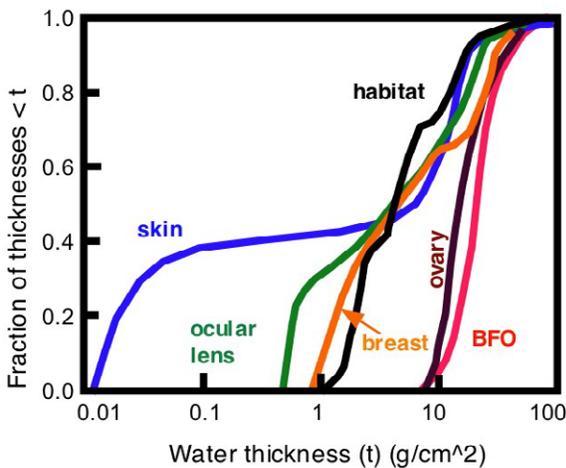
Figure 9. Cumulative thickness distributions for habitat targetpoint and body target points used by Anderson et al. (2005) (figure9.jpg).

with providing airlocks for crew EVA and radiation protection. The habitat is capable of autonomous landing and system startup following the landing. The facility consists of three levels with a total pressurized volume of 240 m^3; it has an outer diameter of 6.5 meters and an inner diameter 6.0 meters. The lowest level houses two two-person airlocks, which can also act as shelters during solar particle events. It also contains an unpressurized porch that crew-members may use to dust off prior to vehicle ingress. The second deck contains the science laboratory and the mechanical and avionics systems. The third floor houses the crew quarters, galley and wardroom. The core structure is designed to be a cylindrical pressure vessel and is approximately 6 meters tall by 6 meters in diameter.

The paper by Anderson et al. (2005) deals only with GCR and does not consider SPE. The free-space GCR flux vs. energy is first calculated for each value of atomic number. They estimate doses within the habitat by modeling transport along various ray directions that interact first with the CO_2 along the slant path through the atmosphere, followed by an appropriate H_2O amount representing the effective habitat wall plus body tissue thickness. The assumption is made that the habitat walls consists primarily of unspecified lightweight materials of high hydrogen content that can be approximated as water. The third material layer is that of the Martian regolith for which transport of the primary GCR field is performed for a thickness of 100 g/cm^2. Since the regolith seems to be only behind the habitat as a source of backscatter, it is not clear why they limited it to 100 g/cm^2 Nevertheless, they claim that backscatter contributed about 8% of the interior dose. Detailed analyses were made for the specific geometry of the assumed habitat as well as placement of crew-members within it. For a fixed Mars atmosphere of 16 g/cm^2, they estimate the dependence of annual interior dose on water shield density as given in Table 6. Anderson et al. (2005) are not very clear on this point, but it appears that the results in Table 6 are before taking into account shielding by the planet itself from below. Therefore, to account for this, the values in Table 6 should probably be divided by two.

The cumulative water thickness distributions used in the analysis are shown in Figure 9.

Anderson et al. (2005) state:

"For a stay of up to three years on Mars, the BFO calculations indicate that GCR exposures remain well below their limit guidelines. It must be noted that the present analysis does not consider contributions from solar proton events or those incurred during transit in order to avoid the complicating factors of vehicle configuration, trajectory options, and SPE shelters. The scenario presented here conservatively assumes a low-density atmosphere and a habitat that provides only inherent shielding from its basic structure (i. e., the pressurized habitat is designed only to provide a 'shirtsleeve' atmosphere)."

The net result was that the calculated dose equivalents inside the habitat on Mars were in the range 20-24 cSv/yr for various body parts with BFO being 20 cSv/yr. When compared to the point estimates of annual allowable exposure (Table 1), these are within an acceptable range. However, when converted to 95% CI doses, the exposure is excessive.

Uncertainty in Planning for Radiation Protection

Introduction

Wilson et al. (2001) discuss uncertainty in planning for radiation protection of astronauts. They state: "Protection against the hazards from exposure to ionizing radiation remains an unresolved issue. The major uncertainty is the lack of data on biological response to galactic cosmic ray (GCR) exposures but even a full understanding of the physical interaction of GCR with shielding and body tissues is not yet available." Recent work underscores this

conclusion (Hada and Sutherland 2006).

Wilson et al. (2001) then go on to state: "The general opinion is that the initial flights should be short-stay missions performed as fast as possible (so-called 'Sprint' missions) to minimize crew exposure to the zero-g and space radiation environment, to ease requirements on system reliability, and to enhance the probability of mission success." However, Wilson et al. (2001) point out that "The short-stay missions tend to have long transit times and may not be the best option due to the relatively long exposure to zero-g and ionizing radiation." But then they state: "On the other hand the short-transit missions tend to have long stays on the surface requiring an adequate knowledge of the surface radiation environment to estimate risks and to design shield configurations." But regardless of the uncertainties involved, there are some aspects that can be firmly concluded. On a day-for-day basis, it is far better to be on the surface of Mars than in space because of the shielding afforded by the planet from the back-side and the atmosphere from the front side. In addition the use of regolith shielding may help protect against SPEs. Furthermore, it is unlikely that propulsion requirements for short stay missions can be met.

Wilson et al. (1993) discuss uncertainty in effectiveness of radiation shields as of 1993. They point out that for low Earth orbit (LEO), the predominant radiation exposure is from electrons and protons. For this radiation, extrapolations based on existing radiobiological data may be adequate for establishing exposure limits.

For galactic cosmic rays (GCR's) and, in particular, for the highly charged, energetic nuclei (HZE particles) that constitute their biologically most significant components, Wilson et al. (1993) state that these quantities may no longer provide an adequate description of the radiation risk. In fact there is evidence that extrapolations from existing radiobiological data are not adequate - also note Hada and Sutherland (2006). In these examples, the notion of a quality factor related to relative biological effectiveness (RBE) becomes meaningless. That is, at doses comparable with those delivered by one or a few particles and for radiation effects that are not present for low linear energy transfer (LET) radiation (e.g., X-rays), the RBE becomes infinite. Thus, new methods to predict the risk resulting from exposure to GCR radiation must be developed. Wilson et al. (1993) go on to state that "in addition to the problems posed by radiation effects that are not observable at reference doses of low LET radiation, risk estimates are uncertain, even for known radiation effects. The current uncertainty in risk predictions is estimated to be as large as an order of magnitude (10- to 1000-percent range). This value is no more than an educated guess obtained with the assumption that the uncertainty of a factor of 10 is the uncertainty in the prediction of shielding effectiveness (a factor of 2 to 3) combined with the uncertainty in predicting biological response to HZE particles (a factor of 4 to 5)."

Cohen (1996) asserts that:

"radiation shielding is the most overlooked feature of proposed interplanetary vehicles. NASA and space industry mission planners consistently underestimate the radiation hazards on a trip to Mars, particularly from GCRs and thus minimize the shielding to protect against this exposure. The conventional wisdom states: 'NASA cannot afford to shield against radiation because the enormous mass penalty will make a Mars mission too expensive.' However, a truly safety-conscious approach insists 'NASA cannot afford NOT to shield effectively against radiation, despite the mass penalties.' It is time for NASA and the space industry to face up to radiation exposure as a major concern for crew health and for their ability to carry out a successful mission and to protect the crew against it.... A careful reading of the requirements for shielding from radiation hazards in interplanetary space indicates the need for substantial omni-directional shielding on the order of 30 g/cm^2."

Managing Lunar Radiation Risks: Cancer, Shielding Effectiveness

The report by Cucinotta et al. (2005) is the first in a three-part series of NASA reports addressing issues related to managing radiation risks for lunar and Mars missions that will focus on preflight safety preparations, including risk projections and shielding effectiveness. The first part addresses cancer risks, the second part will address acute radiation risks from solar particle events (SPEs), and the third part will deal with non-cancer risks including damage to the central nervous system (CNS). Radiation risks include carcinogenesis, degenerative tissue effects such as cataracts or heart diseases, and acute radiation syndromes. Other risks, such as damage to the CNS, are a concern for HZE nuclei.

The following is abstracted from Cucinotta et al. (2005). Recently, NASA recognized that projecting uncertainties in cancer risk estimates along with point estimates should be a requirement for ensuring mission safety because point estimates alone have limited value when the uncertainties in the factors that enter into risk calculations are large. Estimates of 95% confidence intervals (CI) for various radiation protection scenarios are meaningful additions to the traditional point estimates, and can be used to explore the value of mitigation approaches and of research that could narrow the various factors that enter into risk calculations. Designing space missions with acceptable levels of cancer risks can take several pathways. Because of the penetrating nature of the GCR and the buildup of secondary radiation in tissue behind practical amounts of all materials, improving knowledge of biological effects to narrow confidence intervals is important to achieve radiation safety goals. Uncertainties for low-LET radiation, such as gamma-rays, have been reviewed several times in recent years, and indicate that the major uncertainty is the extrapolation of cancer effects data from high to low doses and dose-rates. Other uncertainties include the transfer of risk across populations and sources of error in epidemiology data

including dosimetry, bias, and statistical limitations. In estimating cancer risks for space radiation, additional uncertainties occur related to estimating the biological effectiveness of protons and heavy ions, and to predicting LET spectra at tissue sites. The limited understanding of heavy ion radiobiology has been estimated to be the largest contributor to the uncertainty for space radiation effects, and radiation quality factors were found to contribute the major portion of the uncertainties (Hada and Sutherland 2006).

Cucinotta et al. (2005) describe calculations of probability distribution functions (PDFs) representing uncertainties in projecting fatal cancer risk from galactic cosmic rays (GCR) and solar particle events (SPEs). The PDFs are used in significance tests of the effectiveness of potential radiation shielding approaches. Using Monte-Carlo techniques, they propagate uncertainties in risk coefficients determined from epidemiology data, dose and dose-rate reduction factors, quality factors, and physics models of radiation environments to formulate cancer risk PDFs. Competing mortality risks and functional correlations in radiation quality factor uncertainties are treated in the calculations. Conventional treatments of radiation effects deal with "excess lifetime risk" (ELR), which is the increased probability that an exposed individual will die from cancer. ELR is defined by the difference in the conditional survival probabilities for the exposed and unexposed groups. In current analyses, career radiation limits are based on fatal cancer risks. For low Earth orbit (LEO) programs, an excess fatal risk of 3% is used as a criterion for dose limits, which are applied using age- and gender-specific dose to risk conversion factors. Although standards for lunar missions are under review at this time, it is expected that cancer risks will be the major component of radiation limits until knowledge on chronic non-cancer risks from radiation are more firmly established. Radiation risk projection models serve several roles; these roles include setting dose-to-risk conversion factors needed to define dose limits, projecting mission risks, and evaluating the effectiveness of shielding or other counter-measures. For mission planning and operations, NASA uses the model recommended in the NCRP Report No. 132 for estimating cancer risks from space. This model employs a life-table formalism, epidemiological assessments of excess risk in exposed cohorts such as the atomic-bomb survivors, and estimates of dose and dose-rate reduction factors and linear energy transfer (LET)-dependent radiation quality factors. Cucinotta et al. 2005) use the "risk of exposure-induced death" (REID) that is the lifetime risk that an individual in the population will die from a cancer caused by his or her radiation exposure. In general, the value of REID exceeds that of ELR by about 10–20%.

In most treatments of radiation effects, a point estimate is made. That is, a "best estimate" is made of the ELR. However, in Cucinotta et al. (2005) the uncertainties in all the elements that feed into the radiation effects calculation are estimated and these are used to generate probability distribution functions. For example, Figure 10 shows the effect of uncertainty in the physics models of radiation

environments on the dose experienced behind 20 g/cm^2 of Al for a hypothetical 600-day Mars "swingby" mission.

Figure 10 indicates that whereas the conventional point estimate would indicate a dose of 0.86 Sv, the uncertainty in this figure is such that to be 95% confident, one should assume a dose of 1.08 Sv. This only includes uncertainty in physics models; it does not include uncertainty in epidemiology data, dose and dose-rate reduction factors, or quality factors. When these uncertainties are included the error bars increase considerably and the divergence between the 95% CI estimate and the point estimate increases markedly.
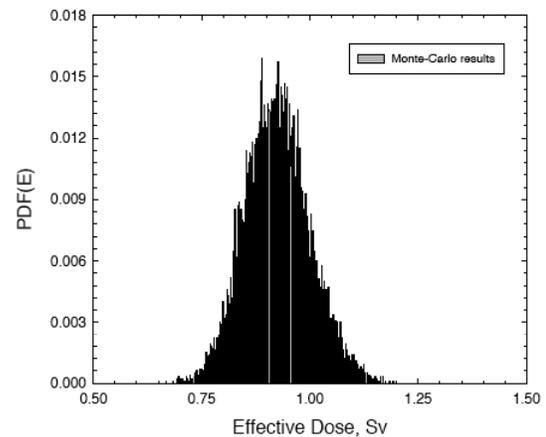
Figure 10. PDF for GCR effective dose for 20 g/cm^2 aluminum shield for 600-d Mars swingby mission. The point estimate is 0.86 Sv, and the 95% confidence intervals (CI) for uncertainties in LET distribution at tissue sites are [0.78, 1.08] Sv. Only uncertainties in physics are included (figure10.jpg). Cucinotta et al. (2005)

Radiation Effects in Lunar and Mars Missions

Mars Design Reference Missions

Several Mars design reference missions (DRMs) were developed by NASA-JSC during the 1990s. The ESAS plan for Mars (Anonymous 2005) is based on the DRM known as "DRM-3" (Drake 1998) that was a modification of a previous NASA-JSC DRM known as "DRM-1" (Hoffman and Kaplan 1997). This was followed by the so-called "Dual-Landers" DRM, but this was never documented and seems to have been discarded by ESAS. In addition, independent Mars DRMs were developed by Robert Zubrin ("Mars Direct") and the Mars Society led by James Burke. None of these DRMs dealt with radiation protection to any significant degree.

DRM-1 acknowledged that two radiation hazards exist, and the first and most dangerous is the probability of a solar proton event (SPE) that is likely to occur during any Mars mission. They acknowledged that SPEs "can rise to the level where an unshielded person can acquire a life threatening

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radiation dosage." However, they stated that "shielding with modest amounts of protective material can alleviate this problem. The task becomes one of monitoring for events and taking shelter at the appropriate time." They then went on to acknowledge GCR as "the other radiation hazard." The authors state that: "The health risk today from radiation exposure on a trip to Mars cannot be calculated with an accuracy greater than perhaps a factor of 10. The biomedical program at NASA has given high priority to acquiring the necessary health data on HZE radiation, including the design shielding materials, radiation protective materials, and SPE monitoring and warning systems for the Mars crew." As it turns out, DRM-1 provided tables of vehicle masses in which the row marked "radiation protection" had zero mass allocated.

According to DRM-1, the trans-Mars habitation element will consist of a structural cylinder 7.5 meters in diameter and 4.6 meters long with two elliptical end caps (overall length of 7.5 meters). JSC's DRM-3 utilized a TransHab that was ~9.7 meters long and inflates to a diameter of ~9.5 meters. Its total mass was estimated at ~24.3 metric tons including the crew and their consumables. DRM-3 does not deal specifically with radiation but it does mention regolith as a possible shield for the surface nuclear reactor. No mass was assigned specifically to radiation shielding.

A reasonable assumption is that two Mars "TransHabs" will be employed, one as the Earth Return Vehicle, and one as the landed habitat. Each of these is assumed to be a cylinder of length 8 m and diameter 8 m with a structural wall thickness amounts to 5 g/cm^2 of aluminum. Due to the shielding effect of stored food, equipment and facilities, additional shielding exists bringing the average over the whole solid angle to roughly 10 g/cm^2. The total surface area of a Mars TransHab is $(\pi \times 8 \times 8 + 2 \times \pi \times 42) = 300 \ m^2 = 3 \times 10^6 \ cm^2$. This value implies that the mass of the TransHab is ~30 mT, which is in line with estimates by design reference missions.

Radiation Analysis

Cucinotta et al. (2005) performed a detailed analysis of radiation effects for several mission scenarios as described in Table 7. They carried out calculations at Solar Minimum and near Solar Maximum. For Solar Maximum calculations, they assumed that the large SPE of August 1972 occurred during the interplanetary part of the mission, and used a solar modulation parameter that is typical of about two years past Solar Maximum, when large SPEs often occur. SPE worst-case risks will be considered in Part II of this series of reports. They note that SPE exposures on the lunar surface are reduced by approximately one-half by the Moon itself, and on the Mars surface by more than one-half due to the planet and the Mars atmosphere. They used a 16 g/cm^2 vertical height for the Mars carbon dioxide atmosphere in their calculations.

Spacecraft typically have aluminum as a major constituent, and transport calculations often scale material thicknesses

under an aluminum-equivalent areal-density $\tau = \rho x$, approximation where ρ is mass density, x is physical thickness, and materials are scaled to aluminum by the ratio of the range of 60 MeV protons or a similar approximation. Cucinotta et al. (2005) provide thickness distributions in aluminum-equivalent depths for the Apollo Command module and several more recent spacecraft used in LEO. Minimal areal-densities of spacecraft such as Skylab, the Space Shuttle, or the International Space Station (ISS) are 2 to 5 g/cm^2. However, averages are in the range from 5-10 g/cm^2 of aluminum-equivalent material. The launch requirements for deep space may require reduced shielding mass compare to these vehicles. Many dose calculations in the scientific literature underestimate the inherent shielding of spacecraft and tissues. Detailed calculations were made for minimally shielded spacecraft of 5 g/cm^2 aluminum and a heavily shielded spacecraft of 20 g/cm^2.

The results of calculations by Cucinotta et al. (2005) are summarized in Tables 8 to 11. As stated previously, conventional treatments of radiation effects deal with "excess lifetime risk" (ELR), which is the increased probability that an exposed individual will die from cancer. Cucinotta et al. 2005) use instead, the "risk of exposure-induced death" (REID) that is the lifetime risk that an individual in the population will die from a cancer caused by his or her radiation exposure. In general, the value of REID exceeds that of ELR by about 10–20%. In the tables that follow, the reported values of REID are the point estimates. However, because of the large uncertainties in these estimates, the 95% confidence intervals (CI) are also given. The high side of the 95% CI may typically be a factor of 3 (or more) higher than the point estimate.

Table 7. Mission Time Lines (Cucinotta et al. 2005)

Exploration mission	Time period	Total days	Deep space days	Lunar or Mars surface days
LEO CEV test	2012–15	6	6 (LEO)	0
Lunar-short	2014–20	14	6	8
Lunar-long	2020–30	90	6	84
Mars swingby*	2030–40	600	600	0
Mars surface	2030–40	1000	400	600

* Mars swingby mission is unlikely to be inherently feasible and affordable.

Cucinotta et al. (2005) also compared aluminum shields with polyethylene and hydrogen shields of 5 and 20 g/cm^2. For constant g/cm^2, they found slight improvements with polyethylene over aluminum but they conclude that, "because of the modest differences between polyethylene and aluminum as GCR absorbers and the large radiobiological uncertainties in cancer risk projection models, the benefits of polyethylene compared to aluminum shielding for GCR cannot be proven at this time." It is notable that other investigators also found HDPE to have

Table 8. Calculations of effective doses, REID, and 95% CI for lunar or Mars missions. Calculations are at Solar Minimum for a 5-g/cm^2 aluminum shield. D = dose (Gy), E = dose equivalent (Sv) ([Cucinotta et al. 2005](#))

Exploration mission	D, Gy	E, Sv	REID (%) [95% CI]
Males (40 y)			
Lunar-long	0.03	0.084	0.34 [0.10, 1.2]
Mars swingby	0.37	1.03	4.0 [1.0, 10.5]
Mars surface	0.42	1.07	4.2 [1.3, 13.6]
Females (40 y)			
Lunar-long	0.03	0.084	0.41 [0.12, 1.5]
Mars swingby	0.37	1.03	4.9 [1.4, 16.2]
Mars surface	0.42	1.07	5.1 [1.6, 16.4]

Table 9. Calculations of effective doses, REID, and 95% CI for lunar or Mars missions. Calculations are at Solar Minimum for a 20-g/cm^2 aluminum shield. D = dose (Gy), E = dose equivalent (Sv) ([Cucinotta et al. 2005](#))

Exploration mission	D, Gy	E, Sv	REID (%) [95% CI]
Males (40 y)			
Lunar-long	0.03	0.071	0.28 [0.09, 0.95]
Mars swingby	0.36	0.87	3.2 [1.0, 10.4]
Mars surface	0.41	0.96	3.4 [1.1, 10.8]
Females (40 y)			
Lunar-long	0.03	0.071	0.34 [0.11, 1.2]
Mars swingby	0.36	0.87	3.9 [1.2, 12.7]
Mars surface	0.41	0.96	4.1 [1.3, 13.3]

significant benefits compared to aluminum. By contrast, hydrogen produced about half the REID % as aluminum at the same g/cm^2 for both Solar Minimum and Solar Maximum conditions.

According to these tables, the 95% CI values are typically 3 to 4 times the point estimates of REID.

[Cucinotta et al. (2005)](#) properly assert that their current estimates are significant improvements over past estimates, but they go on to state that these estimates should be viewed as preliminary because a number of factors require further study. They state: "For exploration missions outside LEO, higher risks from radiation may be unavoidable because of the longer durations where high GCR exposures will occur and the potential risks from SPEs." They also indicate that "career radiation limits and shielding requirements could also be impacted by new knowledge of fatal non-cancer risks from radiation exposure such as heart disease or damage to the central nervous system (CNS)."

Radiation Analysis in the ESAS Final Report

Introduction. The recently released ESAS Report ([Anonymous 2005](#)) provided an extensive discussion of radiation. Since there is considerable overlap between the ESAS Report and the preceding sections of this paper, we will mainly focus here on unique aspects of the ESAS Report that embellish, add to, or differ from the preceding sections of this paper.

Table 10. Calculations of effective doses, REID, and 95% CI for lunar or Mars missions. Calculations are near Solar Maximum assuming 1972 SPE in deep space segment of mission with a 5-g/cm^2 aluminum shield. D = dose (Gy), E = dose equivalent (Sv) ([Cucinotta et al. 2005](#))

Exploration mission	D, Gy	E, Sv	REID (%)	95% CI
Males (40 y)				
Lunar-long	0.45	0.69	2.7	[0.95, 7.6]
Mars swingby	0.62	1.21	4.4	[1.5, 13.1]
Mars surface	0.66	1.24	4.8	[1.6, 14.2]
Females (40 y)				
Lunar-long	0.45	0.69	3.3	[1.1, 9.3]
Mars swingby	0.62	1.21	5.7	[1.8, 17.1]
Mars surface	0.66	1.24	5.8	[2.0, 17.3]

Table 11. Calculations of effective doses, REID, and 95% CI for lunar or Mars missions. Calculations are near Solar Maximum assuming 1972 SPE in deep space segment of mission with a 20-g/cm^2 aluminum shield. D = dose (Gy), E = dose equivalent (Sv) ([Cucinotta et al. 2005](#))

Exploration mission	D, Gy	E, Sv	REID (%)	95% CI
Males (40 y)				
Lunar-long	0.04	0.09	0.36	[0.12, 1.2]
Mars swingby	0.22	0.54	2.0	[0.60, 6.8]
Mars surface	0.25	0.60	2.4	[0.76, 7.8]
Females (40 y)				
Lunar-long	0.04	0.09	0.43	[0.13, 1.4]
Mars swingby	0.22	0.54	2.5	[0.76, 8.3]
Mars surface	0.25	0.60	2.9	[0.89, 9.5]

The ESAS Report ([Anonymous 2005](#)) states:

"Unlike LEO exposures, which are often dominated by solar protons and trapped radiation, interplanetary exposures may be dominated by GCRs, for which there is insufficient data on biological effects. Consequently, risk prediction for interplanetary space is subject to very large uncertainties, which impact all aspects of mission design. "

The ESAS Report ([Anonymous 2005](#)) goes on to state that:

"Short lunar stay strategies must include integrating the ALARA requirement into the vehicle design and operations; recommending the use of carbon composites in vehicle structures, shielding, and components early in the design; and providing recommendations on design optimization. Sortie times may also be restricted by worst-case SPE definition

and EVA suit shielding properties. Local shielding is recommended to minimize risks, and mission planning must consider trade-offs (e.g., habitat shelter shielding versus surface abort). Long lunar stay missions will likely require increased shielding over a short stay and the development of strategies to reduce chronic risk and GCR impacts. The inclusion of previous exposures for crew selection also becomes more important (astronauts with prior lunar or ISS missions)."

The ESAS Report (Anonymous 2005) appears to have adopted the 95% CI requirement, for they state:

"The LEO career limit is the probability of 3 percent additional risk of lifetime lethal cancer within a 95 percent confidence interval."

The ESAS radiation study (Anonymous 2005) addressed the relationship between shielding mass, dosage, and crew risk for the CEV in three analysis cycles and further work is planned for the future.

ESAS Radiation Analysis Cycle #2. The ESAS Report (Anonymous 2005) describes the results of an Analysis Cycle #2 that addressed the relationship between shielding mass, dosage, and crew risk for the CEV:

"The probability of an event was determined using the two largest events on record for which accurate spectral information is available. The August 1972 event is generally accepted as the benchmark SPE in observable history. The confidence of not exceeding the August 1972 event fluence level above 30 MeV on a 1-year mission near the Solar Maximum is roughly 97 percent. To achieve a 99.5 percent confidence interval above 30 Million Electron Volts (MeV), one must assume a fluence level about four times the August 1972 event. The probability of an event that would exceed the current LEO limits within any 1-week mission was estimated at 0.2 percent. The estimated probability of an SPE that could cause debilitation (1.5 times the August 1972 event) was estimated at roughly 0.03 percent. A debilitating event was identified as a dose that would cause vomiting within 2 days in 50 percent of the total population. The estimated probability of a catastrophic event (4 times the August 1972 event) causing death within 30 days was estimated at roughly 0.01 percent. These estimates were developed using historical data with no statistical analysis of the frequency distribution of the event."

Analysis Cycle #2 used a CAD model of the CEV for short-term sortie missions. The internal systems represented in this CEV model were of fairly high fidelity. However, the outer hull of the vehicle was of lower fidelity, represented by an aluminum pressure shell and an assumed high-density polyethylene (HDPE) radiation shield. Mass sensitivity curves illustrating the reduction in radiation exposure to crew-members within the CEV with increasing shield augmentation were calculated for two design case SPEs:

Four times the proton fluence (no time dependence) of the August 1972 event was evaluated, as well as four times the proton fluence of the September 1989 event. It was assumed that only one large design-basis SPE occurred during the specified mission length. GCR was not addressed because of the short mission duration for sortie missions. A radiation dose calculation was performed for the skin, eye, and BFO using the equivalent spheres approximation. This approximation assumes a tissue depth of 0.01, 0.3, and 5 cm for the skin, eye, and BFO dose calculations, respectively. It is claimed that use of the equivalent spheres approximation can result in a two-fold overestimation of dose as compared to the more accurate computer-aided manufacturing (CAM) model that will be used in later analysis cycles. The results are shown in Table 12 for the Apollo Command Module, a CEV with an aluminum pressure shell, and the CEV with 5 g/cm^2 of HDPE added for radiation protection. Note that the density of HDPE is about 0.95 so that 5 g/cm^2 corresponds to a thickness of about 5 cm, or 2 inches. It is stated that the Apollo Command Module, which corresponds to a thickness of approximately 5 g/cm^2 was modeled with a CAM process. Even so, despite the tendency for the CAM to be more accurate, it is difficult to understand why the doses are so much greater for an aluminum CEV than for the Apollo Command Module since it is hard to believe that the CEV pressure shell is much less than 5 g/cm^2. The dose equivalents in Table 12 are very high compared to other estimates in the literature. At first it appeared that the results in Table 12 may have been the result of a typographical error, but Figure 11 shows that the ESAS Report corroborates the high estimates of Table 12. Note that the estimated BFO dose equivalent from a 4X major SPE is considerably greater than the 30-day allowable dose equivalent in Table 1.

The ESAS Report (Anonymous 2005) then went on to use these calculated dose equivalents to make probabilistic estimates of risk and loss-of-life for a 35- and 45-year-old males and females. A three-layer version of aluminum or graphite/epoxy, polyethylene, and tissue was employed. No previous occupational radiation exposure was assumed for any of these representative crew-members. The radiation limit was taken as a 3 percent fatal cancer probability within a 95 percent confidence interval. The calculation considers age/gender, radiation quality, SPE dose-rate, shielding materials, and prior ISS/CEV missions. The results are displayed in Tables 13 and 14.

According to Table 13, the excess lifetime risk for the aluminum CEV exceeds the allowable 3% figure by a significant amount. When 5 g/cm^2 of HDPE is added, the point estimates drop below 3% but the high end of the 95% CI remains above 3%. There is an apparent conflict between Table 12 and Figure 11 on the one hand, and Table 13 on the other hand, that is difficult to resolve. Presumably, the LEO limit shown in Figure 11 corresponds to a 3% excess lifetime risk. Since the estimated dose equivalents in Figure 11 far exceed the allowable, it seems contradictory that the calculated risks in Table 13 are estimated to be as low as they

Table 12. Analysis Cycle #2 radiation dose calculations for aluminum CEV with high-density polyethylene (HDPE) supplemental shielding. *Note: Two columns for CEV represent two locations within the vehicle. (Anonymous 2005)

Organ Dose 4x 1972 SPE	Apollo	Aluminum CEV*		CEV+Poly 5 g/cm^2	
Skin (Sv)	10.36	42.63	47.75	12.25	13.72
Eye (Sv)	8.20	32.54	36.44	9.71	10.87
BFO (Sv)	1.39	4.17	4.67	1.56	1.73
Organ Dose 4x 1989 SPE		Aluminum CEV*		CEV+Poly 5 g/cm^2	
Skin (Sv)		23.40	25.98	7.10	7.88
Eye (Sv)		16.57	18.39	5.42	6.01
BFO (Sv)		2.73	3.03	1.29	1.40
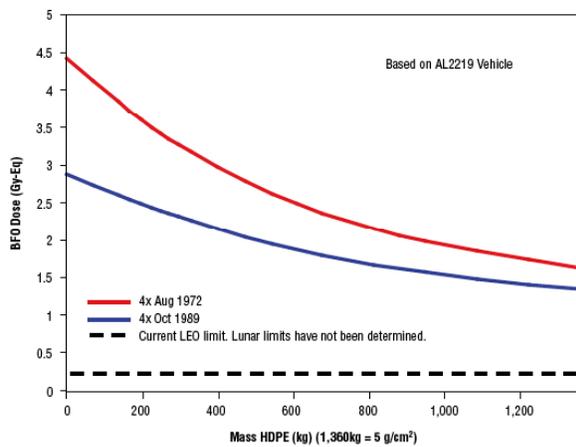
Figure 11. BFO dose equivalent as a function of HDPE thickness. Note that 5 g/cm^2 of HDPE corresponds to about 2 inches of thickness, and leads to a CEV shield mass of 1360 kg. This implies that the surface area of the CEV is 1,360,000/5 = 2.72 x 10^5 cm^2 (figure11.jpg). (Anonymous 2005)

are. One would think that for the excessive doses shown in Figure 11, the risks in Table 13 might be much higher. It is difficult to resolve this discrepancy.

The ESAS Report (Anonymous 2005) also estimated acute risks using the Nuclear Regulatory Commission (NUREG) fatal accident risk model. However, the NUREG model is unable to properly evaluate acute risks (mortality or debilitating sickness) below a 10 percent probability and therefore the results are dubious. Also, microgravity research suggests that altered immune and stress responses could skew the lower probabilities of dose responses to reduced dose levels complicating the evaluation of acute risk near the threshold (less than 10 percent risk). Nevertheless, the ESAS Report concluded that depending on the baseline CEV design, acute risks are possible for an event with the 1972 spectral characteristics and two to four times the (>30 MeV) fluence as shown in Table 14. Unfortunately, the ESAS

Table 13. Excess lifetime cancer risk for shielded and unshielded CEV as a function of crew member age and gender. "% Risk" indicates point estimates, while numbers in brackets represent low and high ends of 95% confidence intervals based on wide error bands in the point estimates. (Anonymous 2005)

4 x 1972 - Equivalent SPE - CEV				
Organ Dose	Aluminum CEV		CEV + 5 g/cm^2 HDPE	
Crew Characteristic	% Risk	95% C.I.	% Risk	95% C.I.
Male 35-yr	9.7	[3.4, 17.5]	1.7	[0.5, 4.7]
Male 45-yr	7.5	[2.7, 16.4]	1.3	[0.4, 3.5]
Female 35-yr	12.1	[4.0, 17.6]	2.1	[0.7, 5.9]
Female 45-yr	9.1	[3.2, 17.3]	1.5	[0.5, 4.3]
4 x 1989 - Equivalent SPE – CEV				
Organ Dose	Aluminum CEV		CEV + 5 g/cm^2 HDPE	
Crew Characteristic	% Risk	95% C.I.	% Risk	95% C.I.
Male 35-yr	6.9	[2.4, 15.8]	2.2	[0.73, 6.0]
Male 45-yr	5.3	[1.9, 13.4]	1.7	[0.57, 4.5]
Female 35-yr	8.6	[2.9, 17.1]	2.8	[0.9, 7.6]
Female 45-yr	6.4	[2.3, 15.3]	2.0	[0.7, 5.6]

Table 14. CEV acute and late risks for various depths of HDPE radiation shielding. (Anonymous 2005)

Aluminum Vehicle 4 x 1972 - Equivalent SPE			
HDPE Depth (g/cm^2)	% Acute Death*	% Sickness	% REID**
CEV-old + 0 g/cm^2	9.5	54	9.1 [3.2, 17.3]
CEV-new + 0 g/cm^2	<1% (#)	<5% (#)	4.4 [1.5, 11.8]
CEV-new + 1 g/cm^2	0	0	3.5 [1.2, 9.7]
CEV-new + 2 g/cm^2	0	0	2.9 [1.0, 8.2]

* Death at 60 days with minimal medical treatment

** Risk of Cancer death for 45-yr-old females

\# Too close to threshold to estimate

Report (Anonymous 2005) does not seem to explain what "CEV-old" and "CEV-new" represent. However, it seems likely that "CEV-old" probably represents the simpler treatment of the CEV done in Radiation Analysis Cycle #2 and "CEV-new" probably represents the more detailed treatment done within Radiation Analysis Cycle #3. (See discussion in first paragraph of the next Section of this paper).

The results presented in Table 14 suggest that without extra shielding, the probability of acute death from an extreme SPE is a cause for concern.

The ESAS team reviewed the radiation analysis with the goal of "reducing the supplemental radiation shielding that was

resulting in a diminishing benefit to the crew. Since the radiation shielding mass is carried round-trip, its mass has one of the greatest mass sensitivity penalties, which identifies it as a candidate for additional analysis."

According to the ESAS Report (Anonymous 2005), the addition of 1360 kg of shielding to the CEV (about 5 g/cm^2) adds about 12-15 mT to the initial mass in LEO (IMLEO). In other words, the "gear ratio" is roughly 10:1.

ESAS engineers and safety and risk analysts then agreed to proceed into a third analysis cycle utilizing a maximum of 2.0 g/cm^2 of supplemental radiation shielding. Note that 2.0 g/cm^2 of HDPE corresponds to 544 kg on the x-axis of Figure 11, and further increases in shielding yield diminishing improvements in dose reduction. The Cycle 3 radiation analysis is discussed in the next section of this paper.

All of the previous material discussed the effects that result if an SPE occurs during a mission. However, it is important to remember that lunar sortie missions are relatively short in duration and that SPEs occur rarely. Therefore, the probability of encountering an SPE during a sortie mission is small. Since other risks (unrelated to radiation) exist in sortie missions that are probable to the extent of up to a few percent, adding massive radiation shields may be inappropriate if the innate probability of encountering a SPE is far smaller than the probability of other serious risks. The ESAS Report then went on to quantify this. They pointed out that "the dose and biological risk data were derived from a 4-times-1972 event that represented a 99.5 percent confidence of not exceeding a fluence level exceeding 30 MeV for a mission duration of 1 year." Therefore, the probability of exceeding the calculated doses is only 0.005.

A major SPE seems to occur perhaps once per 11-year solar cycle, or once per three-year Solar Maximum, and if an SPE lasts a few days, the probability per day of encountering a major SPE during Solar Maximum is innately equal to [a few days] divided by [the duration of Solar Maximum (roughly 1200 days, give or take a few hundred)], or a few tenths of a percent. Let us call this P1 and assume for the sake of argument, that it is equal to 0.002. For a 16-day lunar mission during Solar Maximum, the probability of encountering a major SPE is 16 x 0.002 = about 3%. This is a non-negligible threat. However, the ESAS Report states:

"Therefore, for a 16-day maximum mission (0.04 year duration), the probability for exceeding a 0.01 percent probability of acute death, a 1.9 percent probability of debilitating sickness, and a 3.4 percent probability of excess cancer risk is itself only 0.005. For 5 g/cm^2 of shielding, these values are either zero or approaching zero."

However, it is difficult to trace the origin of these figures and they do not seem to tally with data presented in tables and figures in the ESAS Report (Anonymous 2005).

Ultimately, the ESAS team decided to:

- Incorporate the use of composite materials in the CEV in addition to an aluminum pressure shell, as part of the cross-sectional skin of the vehicle.
- Carry out additional analysis to more accurately model the CEV cross-section and to further investigate the range of supplemental radiation shielding in the range from 0 to 2.0 g/cm^2.

These decisions formed the basis of the Cycle 3 radiation analysis presented in Section 4.2.5 of the ESAS Report (Anonymous 2005).

ESAS Radiation Analysis Cycle #3. The Analysis Cycle #3 radiation study focused on creating a better approximation to the actual CEV in order to generate a more refined and realistic radiation evaluation. This higher fidelity model included the addition of a thermal protection system (TPS), composite outer mold line skin, and insulation to the structure of the vehicle (in addition to the original HDPE radiation shield and aluminum hull). The inclusion of these structures had a significant impact on the amount of radiation shielding the vehicle inherently provided. For comparison purposes, the shield distribution was generated in the same fashion and using the same points as the Analysis Cycle 2 evaluation. Calculations for the historical large SPEs were repeated with the refined CEV configuration and the values of thin HDPE (1 or 2 g/cm^2) augmentations. The results are shown in the lower three rows of Table 14. As shown in Table 15, the predicted 95 percent confidence interval doses would exceed allowable exposure for most astronauts with no prior occupational exposure below age 45-yr for the revised CEV with 0 or 1 g/cm^2 polyethylene augmentation shielding. For astronauts with prior ISS exposure, more stringent constraints will occur. With the 2 g/cm^2 HDPE augmentations, 95 percent CI doses would exceed allowable levels for a significant fraction of the astronaut population. Higher constraints are possible if fatal non-cancer risks are added to the NASA legal dose limits. As before, it is difficult to understand why these predicted biological impacts are as low as they are considering that Table 12 and Figure 11 indicate an SPE dose far in excess of the allowable level.

The ESAS Report (Anonymous 2005) points out that estimation of acute risk is difficult because of lack of radiobiological data at the 0-10 percent probability levels and the potential impacts of immune depression and stress on the dose-response. It is claimed that: "addition of HDPE would likely prevent the occurrence of acute risks from a historically large SPE."

The ESAS team adopted a policy of "risk leveling" in order to protect astronaut crews roughly equally from all known sources of injury or death. That is, it would not make sense to require far lower probabilities of injury or death from radiation than already exists in the mission from other sources (propulsion, maneuvers, ...) The ESAS team viewed

Table 15. Risk of Fatal Cancer for Large SPEs. All data are in %. Figures outside brackets are point estimates. Figures in brackets represent range of 95% CI.

Risk of Exposure Induced Death for 45-yr Females					
Nx '72 SPE	Con*	CEV-old with 0 g/cm² HDPE	CEV-new with 0 g/cm² HDPE	CEV-new with 1 g/cm² HDPE	CEV-new with 2 g/cm² HDPE
4x	99.1	9.1 [3.2,17.3]	4.4 [1.5,11.8]	3.5 [1.2,9.7]	2.9 [1.0,8.2]
3x	98.5	6.9 [2.4,16.0]	3.3 [1.1,9.2]	2.6 [0.9,7.4]	2.2 [0.7,6.2]
2x	97.0	4.7 [1.6,12.5]	2.2 [0.8,6.3]	1.7 [0.6,5.0]	1.5 [0.5,4.2]
1x	93.0	2.4 [0.8,6.7]	1.1 [0.3,3.2]	0.9 [0.3,2.5]	0.7 [0.2,2.1]

Con = Confidence that this level will not be exceeded.

the radiation risk as having both an acute short-term effect that could result in loss of mission (LOM) and loss of crew (LOC) and a long-term effect of excess cancer risk due to exceeding monthly or career dose limits. Acute sickness was conservatively judged to incapacitate the crew to the extent that they could not perform any of their functions, which would lead to LOM and LOC due to their inability to act. The ESAS team sought to arrive at a solution that produced near-zero percent probability of acute death or sickness and that did not violate 30-day or career limits for an event with a probability of occurrence equal to that of other LOC risks for a sortie-duration lunar mission. However it is not clear why they did not include annual limits. For longer-duration lunar outpost missions, this analysis would have to be repeated to determine the proper amount of surface habitat shielding required to achieve this same level of protection. The ESAS Report (Anonymous 2005) then goes on to state:

"In order to establish the probability of an SPE occurrence that would exceed a fluence of 30 MeV, a 9-day mission duration was chosen as the average length of time a crew would inhabit the CEV during a sortie-class lunar mission. For longer mission durations, these numbers would increase. Table 16 relates the probability of occurrence of a 30 MeV SPE to the biological effects (acute effects and long-term dose) for 0, 1 and 2 g/cm² of supplemental HDPE shielding for a 9-day CEV mission. At 2 g/cm², all acute effects are zero and long-term doses are within limits until events with a probability of occurrence of 1 in 2,500 (0.04 percent) missions are encountered. With 1 g/cm² of shielding, acute effects are again all zero, but 30-day limits are violated once in every 1,428 (0.07 percent) missions. With all supplemental shielding removed, acute health effects begin to appear once in every 1,428 (0.07 percent) missions, while 30-day limits are violated once in every 588 (0.17 percent) missions."

The choice of 9 days for mission length seems unrealistic. Including transits to the Moon, transfers, maneuvers and a seven-day surface stay, a mission of 16 days duration (as was

used in Radiation Analysis Cycle #2) would seem to be the minimum that should be considered, and depending on requirements for loitering to avoid plane changes, could be longer. Nevertheless, column 3 of Table 16 provides an estimate of the probability of encountering SPEs of various fluence for a 9-day mission. While it might be true that the time spent in the CEV is about 9 days under the most favorable circumstances, there is an additional 7 days on the lunar surface, often involving EVA. Since the surface habitat is likely to less heavily armored than the CEV, the total exposure of the crew is more like 16 days. Furthermore, in some lunar scenarios, the crew must "loiter" in the lunar vicinity to avoid the propulsion requirements for certain plane changes, and this could add to the required exposure time. For a 16-day mission these probabilities would scale linearly. The next four columns in Table 16 give the estimates of biological impact if such events do occur. The data for 4x are apparently taken from Table 13. The data in the career limit and 30-day limit columns appear to be based on the following scheme:

a) If both the point estimate and the 95% CI estimate violate the requirement, the entry is "Yes."

b) If neither the point estimate nor the 95% CI estimate violate the requirement, the entry is "No."

c) If only the 95% CI estimate violates the requirement, this is so noted.

However, the data provided in Table 16 with italic text are clearly the result of a typographical error; they should all be zeros and the data in the cell with bold text appears to be wrong; it almost surely should be: "No (95% Yes)."

In the cases of acute death or sickness, radiation exposure has an effect equal to any other risk that results in LOC. For long-term dose violations, the effect may be an increased probability of lifetime cancer risk to the crew-members, but for the purpose of the ESAS analysis, it was conservatively considered to be an LOC risk as well. The complete lunar sortie mission risk analysis is presented in Section 8, Risk and Reliability, of the ESAS report (Anonymous 2005). The analysis details many of the events that could result in LOC, many of which are large-energy change events such as launch, planetary injection or insertion maneuvers, or planetary landings. Other events are lifetime issues associated with vehicle systems. As a group, the individual risks that result in LOC occur in the 1:100 to 1:1000 range (1.0 to 0.1 percent individual probability of occurrence).

The ESAS team concentrated on radiation risks that placed the probability of loss of crew *P(LOC)* within this range (and preferably nearer to 0.1 percent). The ESAS team used Table 16 for the statistical probabilities. The ESAS Report claims that the 1% probable event has no [serious] adverse biological effects and the 0.17% SPE has no acute or lifetime biological effect even when no supplemental shielding is used on the CEV. These conclusions would be in consonance with Table 16 if the point dose is used. But if the

Table 16. SPE Risks to Crew (Acute and Long-term Dose) as a Function of Supplemental Shielding for a 9-Day CEV Mission as provided by ESAS Report (Anonymous 2005). There appear to be some typographical errors. Data in cells with italic text should probably be zeros. Data in cell with bold text should probably be "No (95% Yes)".

CEV with 0 g/cm² HDPE						
Nx1972 Event	F (>30 MeV) 10⁹	% Probability for 9-Day mission	Acute Death	Acute Sickness	Career Limit Violation	30-Day Limit Violation
4x	20	0.02	<1%	<5%	Yes	Yes
3x	15	0.04	0	<1%	Yes	Yes
2x	10	0.07	0	0	No (95% Yes)	Yes
1x	5	0.17	0	0	No (95% Yes)	No
1% Event	1.5	1.00	0	0	No (95% Yes)	No
CEV with 1 g/cm² HDPE						
Nx1972 Event	F (>30 MeV) 10⁹	% Probability for 9-Day mission	Acute Death	Acute Sickness	Career Limit Violation	30-Day Limit Violation
4x	20	0.02	0	0	Yes	Yes
3x	15	0.04	0	0	No (95% Yes)	Yes
2x	10	0.07	0	0	No (95% Yes)	Yes
1x	5	0.17	0	0	No	No
1% Event	1.5	1.00	0	0	No	No
CEV with 2 g/cm² HDPE						
Nx1972 Event	F (>30 MeV) 10⁹	% Probability for 9-Day mission	Acute Death	Acute Sickness	Career Limit Violation	30-Day Limit Violation
4x	20	0.02	*<1%*	*<5%*	Yes	Yes
3x	15	0.04	*0*	*<1%*	**Yes**	Yes
2x	10	0.07	0	0	No (95% Yes)	Yes
1x	5	0.17	0	0	No	No
1% Event	1.5	1.00	0	0	No	No

95% CI is used as the ESAS Report states it should, then according to the table, when no shielding is used, the 1% probable event and the 0.17% SPE do have lifetime biological effects. The ESAS Report (Anonymous 2005) points out that it is not until the mission encountered the 0.07% probable SPE "that the first of the Next Hop Resolution Protocol (NHRP) limits were exceeded" - although it is not clear what this means. Clearly from the table, there are significant biological effects for such a 0.07% SPE. However, since all of these conclusions were based on a 9-day exposure, and even a 16-day exposure is probably optimistic, all of the probabilities in column 3 of Table 16 should be doubled for a sortie mission. Therefore, using the 95% CI limits and a 16-day duration, one would conclude that:

- The 2% probable event has no serious adverse biological effects provided that at least 1 g/cm2 of HDPE shielding is used.

- The 0.34% probable event has no serious adverse biological effects provided that at least 1 g/cm2 of HDPE shielding is used.

- The 0.14% probable event has significant adverse biological effects that even 2 g/cm2 of HDPE shielding cannot mitigate.

The ESAS team recommended that no supplemental radiation protection was required for the CEV. The ESAS Report (Anonymous 2005) states:

"With the inherent shielding properties of the CEV structure alone, all radiation effects, less one, show a lower probability of occurrence than equivalent LOC risks; additionally, the one with the greatest probability of occurrence falls within the low end of the range of equivalent LOC events. For the CEV without supplemental shielding, acute effects would occur less than once in every 1,428 missions (<0.07 percent), career dose limits would be exceeded less than once in every 1,428 missions (<0.07 percent), and 30-day dose limits would be exceeded less than once in every 588 missions (<0.17 percent)."

As before, if the duration is extended to 16+ days and the 95% CI limits are adopted instead of the point estimates, this picture would change significantly. In this case, without supplemental shielding, the 30-day limit would likely be exceeded for a 2% probable event. Use of 1 g/cm² of HDPE would eliminate the risk for 2% events but not the risk for 0.14% events. Therefore it would appear that the ESAS Report may have reached the conclusion that no shielding is required based on optimistic assumptions, whereas it appears that a moderate amount of shielding is needed. Evidently, CEV mass is a critical commodity and ESAS is highly motivated to reduce mass. The ESAS Report (Anonymous 2005) states:

Table 17. Summary of Estimates of GCR Doses in Space.

Reference	Quoted in this paper	Location and conditions	Comments
Simonsen (1997)	Figure 1	In space behind various shields	5-cm dose point estimates
Tripathi et al. (2001)	Figure 2	In space behind Al shields	BFO dose point estimates
Clowdsley et al. (2004)	Figure 3	In space behind Al or HDPE shields - Solar Minimum	Spherical shielding
Cucinotta et al. (2005)	Figure 5	In space behind various shields	Shows less benefit of HDPE over AL than other investigators
Simonsen (1997)	Figure 7	Behind variable thickness of lunar regolith	Shows Z-dependence
Simonsen (1997)	Figure 8	On surface of Mars after passing through atmosphere and various thicknesses of regolith	Not much benefit from regolith after atmosphere takes out low energy components of GCR
Simonsen (1997)	Table 5	On surface of Mars inside habitats	BFO dose point estimates
Anderson et al. (2005)	Table 6	On surface of Mars after passing through atmosphere and various thicknesses of water shielding	BFO dose point estimates

Table 18. Summary of Estimates of SPE Doses in Space.

Reference	Quoted in this paper	Location and conditions	Comments
Clowdsley et al. (2004)	Figure 4	In space behind Al or HDPE shields - Solar Minimum	4X 1989 SPE
Cucinotta et al. (2005)	Figure 5	In space behind various shields	1972 SPE
Simonsen (1997)	Figure 6	Behind various thicknesses of lunar regolith	1956, 1960 and 1972 SPEs
Simonsen (1997)	Figure 8	On surface of Mars after passing through atmosphere and various thicknesses of regolith	"SPE"
Simonsen (1997)	Table 3	In lunar habitat	1956, 1960 and 1972 SPEs
Simonsen (1997)	Table 4	In lunar habitat	1956 SPE
Simonsen (1997)	Table 5	On surface of Mars inside habitats	1956, 1960, 1972, 1989 SPEs
ESAS Report (Anonymous 2005)	Table 12	Within CEV	4X 1972 SPE
ESAS Report (Anonymous 2005)	Figure 11	Behind HDPE shielding	4X 1972 and 4X 1989 SPEs

"Supplemental radiation shielding ultimately has an effect on the performance of the entire transportation system. Any mass associated with the CEV must travel round-trip from Earth to lunar orbit and back. Thus, the performance sensitivity is second only to mass that travels round-trip to the lunar surface.... With a performance impact of almost 500 kg for every g/cm^2 of shielding added, the CEV design should seek to minimize supplemental radiation shielding. Additional configuration studies should continue to be performed to further reduce the dose to crews by optimizing the arrangement of crew, fuel, and stowage."

The ESAS Report (Anonymous 2005) points out that each 1 g/cm^2 of HDPE added to the CEV adds about 500 kg of mass to the CEV. The ESAS Report claims that adding ~ 500 kg to the CEV adds about 750 kg to the trans-lunar injection mass (TLI). This does not seem to be correct

because the required mass in TLI is roughly triple the mass returned toward LEO. Hence adding 500 kg to the CEV should increase the TLI mass by about 1500 kg.

Summary

There are many estimates of radiation doses in the literature and it is difficult to compare them directly. Sources for finding data on doses in specific locations and conditions are summarized for GCR in Table 17 and for SPEs in Table 18. In addition, Tables 8 to 11 provide estimates for entire mission sequences.

Estimates of GCR Dose

The GCR BFO dose equivalent in space behind various shields was estimated by various investigators as shown in Figures 1, 2, 3 and 5. The following conclusions can be drawn:

- In free space the point estimate of GCR dose equivalent without shielding is about 0.17 cSv/day at Solar Minimum and roughly half that level at Solar Maximum.

- The effect of shielding on GCR is non-linear. Moderate amounts of shielding remove some low energy components but further addition of shielding produces diminishing returns because high energy components are penetrating.

- Estimates of the effects of various thicknesses of shielding vary from investigator to investigator. Cucinotta et al. (2005) find shielding to be less effective than other studies, and they also find that the benefits of HDPE over aluminum are less than found by other studies.

- The consensus seems to be that a 20 g/cm^2 aluminum shield will reduce the point estimate of Solar Minimum dose from about 0.17 cSv/day to about 0.13 cSv/day, and 20 g/cm^2 of HDPE will reduce the point estimate of Solar Minimum dose to perhaps 0.11 cSv/day.

- Conversion of these point estimates to 95% confidence interval doses requires extensive modeling. A rough approximation is to simply multiply the point estimates by ~3.5. If this is done, the 95% CI doses at Solar Minimum are estimated to be 0.60 cSv/day in free space, 0.46 cSv/day behind 20 g/cm^2 of aluminum, and 0.39 cSv/day behind 20 g/cm^2 of HDPE.

- It would take 109 days of exposure behind 20 g/cm^2 of aluminum to reach the annual allowable limit of 50 cSv during Solar Minimum (see Table 1). The dose in a 200-day transit to Mars will exceed the annual limit.

Estimates have also been made for GCR doses on the lunar and Mars surfaces.

Lunar regolith is roughly about as effective against GCR as aluminum for the same thickness measured in g/cm^2. In addition, the Moon itself blocks 50% of the GCR. On the surface of the Moon, it is expected that the GCR 95% CI dose at Solar Minimum will be roughly:

- 0.3 cSv/day for an exposed astronaut in EVA

- 0.23 cSv/day behind 20 g/cm^2 of aluminum

- 0.18 cSv/day behind 40 g/cm^2 of aluminum and regolith

An astronaut spending 6 months on the lunar surface, mainly in shelters, will narrowly fit within the annual allowable guideline of 50 cSv.

The Martian atmosphere reduces the GCR dose received at the surface but additional shielding (aluminum or regolith) is relatively ineffective in further reducing the radiation dose. Simonsen (1997) estimates that the Mars atmosphere reduces the GCR dose by 30% at the surface, and taking into account shielding by the planet itself, we may conclude that the 95% CI GCR dose on the surface of Mars is roughly 0.7 × 0.5 × 0.60 cSv/day, or about 0.21 cSv/day. However, neither aluminum nor regolith shielding is very effective at reducing this. Over the course of a year, the accumulated dose is about 77 cSv, which exceeds the annual allowable of 50 cSv. The

GCR dose estimates in Table 5 by Simonsen (1997) for a Mars habitat are about half of what we have estimated herein. However, the estimates in Table 6 by Anderson et al. (2005) are considerably higher than those estimated herein.

Estimates of SPE Dose

Various investigators have modeled the effects of several major SPEs. The recent ESAS Report (Anonymous 2005) has concentrated on the 1972 SPE, and has emphasized a worst-case assumption of a hypothetical SPE with energy four times that of the 1972 SPE.

It is clear from various studies that exposure to the full brunt of a major SPE would not only have serious implications for shortening of life due to cancer, but would also have immediate acute effects. Fortunately, even small amounts of shielding will reduce the effective dose exponentially. However, adding additional shielding produces diminishing returns. Ultimately, the residual dose behind shields must be estimated and compared with allowable levels. In general, the critical limitation on SPE doses is the 30-day limit of 25 cSv (see Table 1).

Clowdsley et al. (2004) find little difference between HDPE and aluminum in reducing the SPE dose (see Figure 4). Behind 20 g/cm^2 of shielding their point estimate is an effective dose of about 30 cSv per event for 4X the 1989 SPE. Cucinotta et al. (2005) find somewhat more divergence between the effects of HDPE and aluminum but more importantly, they find that the dose equivalent decreases significantly as more shielding is added (see Figure 5). Behind about 20 g/cm^2 of aluminum, their estimated point dose due to the August 1972 SPE is about 5 cSv per event. Simonsen (1997) examined three SPEs, and it was found that the effect of shielding differed considerably from SPE to SPE (see Figure 6). The crossing point where all three SPEs yield the same point estimate is about 20 g/cm^2 of aluminum, where the point estimate is about 30 cSv/event. These point estimates are comparable to the 30-day limit of 25 cSv, but it is likely that the 95% CI doses will greatly exceed the allowable limit.

Simonsen (1997) prepared point estimates of SPE doses within a habitat utilizing regolith for additional shielding on the lunar surface (Tables 3 and 4). The point estimate for the 1956 SPE was 7.5 cSv per event. This would likely lead to a marginal 95% CI dose compared to the 25 cSv limit.

Simonsen (1997) prepared point estimates of SPE doses within a habitat on the surface of Mars for various SPEs. In the worst case (1956 SPE), the point estimate is about 10 cSv but for other SPEs, it is lower.

The ESAS Report (Anonymous 2005) prepared point estimates of the BFO dose due to 4X the 1972 SPE within the CEV. Their results are anomalously high at 130 to 300 cSv (see Table 12).

Lunar Missions

For lunar missions, we assume that:

- A sortie mission with 4 day transits to and from the Moon and 14 days in the vicinity of the Moon, half on the surface and half in orbit involved in loitering or maneuvering. (The potential need for loitering to avoid propellant-demanding plane changes is discussed in Anonymous (2004).) The total elapsed time is 22 days with 15 days in space and 7 days on the surface.

- An outpost mission with 4 day transits to and from the Moon, and 90 or 180 days on the Moon.

Transits to the Moon. For the short transit times involved in transfers to and from the Moon, GCR exposure is clearly lower than the 30-day limit of 25 cSv. Hence no additional radiation shielding is needed to compensate for GCR.

During Solar Maximum there is a possibility of a major SPE and even with fairly heavy shielding, the likely 95% CI dose will exceed the 30-day allowable. If such an SPE occurs, the biological effect depends on the assumed intensity of the SPE as well as the details of the biological and physical models. The ESAS Report (Anonymous 2005) has typically assumed worst-case SPEs with 4 times the intensity of the 1972 event. According to Table 12 and Figure 11, the dose equivalent would be very high. However this table and figure are out of line with other estimates. Table 13 seems more credible. According to this table, the excess lifetime cancer risk would be >> 3% without shielding, and > 3% with 5 g/cm^2 of shielding based on 95% CI doses.

However, the probability of encountering a major SPE in a 22-day sortie to the Moon during Solar Maximum is small. An overly simple estimate is that if one such SPE occurs per 11-year solar cycle, the probability of encountering such an SPE (1/11)(22/900) ~ 0.2% during Solar Maximum (assuming the duration of Solar Maximum is about 900 days within a cycle). The ESAS Report (Anonymous 2005) has estimated the probability of encountering various SPE events during a 9-day mission (see Table 16). If we multiply their probabilities by (28/9) to account for the longer duration we assume here, they would have predicted that the probability of an event depends on its energy, with the probabilities for 22 days during Solar Maximum being:

- 4X 1972 SPE event   0.05%
- 2X 1972 SPE event   0.16%
- 1X 1972 SPE event   0.4%
- 0.3X 1972 SPE event   2.4%

Therefore, the biological impact would be significant if a major SPE were encountered during transit to the Moon, but the probability of this occurring is fairly small.

Dose on the Moon. We have previously estimated the 95% CI GCR dose on the lunar surface:

- 0.3 cSv/day for an exposed astronaut in EVA
- 0.23 cSv/day behind 20 g/cm^2 of aluminum

- 0.18 cSv/day behind 40 g/cm^2 of aluminum and regolith

An astronaut spending 6 months on the lunar surface, mainly in shelters, will narrowly fit within the annual allowable guideline of 50 cSv.

The SPE 95% CI dose was discussed in the previous section. Serious health consequences would result from occurrence of a major SPE. The probability of such an occurrence during a 6-month lunar stay would be about (180/9) = 20 times the probabilities estimated in the ESAS Report (see previous section). Hence the probabilities appropriate to a 6-month lunar stay during Solar Maximum are:

- 4X 1972 SPE event   1.2%
- 2X 1972 SPE event   4%
- 1X 1972 SPE event   10%
- 0.3X 1972 SPE event   60%

It would seem prudent therefore to limit the length of stay on the Moon during Solar Maximum to well under 6 months.

Lunar Mission Summary. For lunar sortie missions, the duration is short enough that GCR creates no serious risks. SPEs do represent a threat, but because they mainly occur near Solar Maximum and because of the short duration of the missions, the probability of encountering a major SPE is about 0.2% during Solar Maximum. Additional shielding on lunar sortie missions would reduce the consequences of a SPE. Without shielding, the crew faces a potential ~0.2% chance of a significant reduction in life expectancy due to cancer. However the 95% CI reduction in life expectancy from a 4X 1972 SPE is greater than 3% even with moderate amounts of shielding. Tables 13 to 15 provide indications of the biological impact.

The ESAS Report (Anonymous 2005) concluded that no shielding is needed on the CEV but this was based on a 9-day mission and use of point estimates. With a longer mission and 95% CI estimates, this conclusion would no longer be supportable.

For lunar outpost missions, the transits to and from the Moon are very short and as in the case of sortie missions, shielding would reduce the risk of shortened life due to an SPE during Solar Maximum. However, even with > 30 g/cm^2 of regolith shielding the 95% CI dose from a major SPE would exceed the 30-day limit on the lunar surface. The probability of encountering such a SPE during Solar Maximum in a 3-month or 6-month rotation is significant. The SPE risk is minimal during Solar Minimum.

The GCR during Solar Minimum is marginal against the annual limit, but this can be mitigated somewhat by use of regolith for shielding the habitat on the surface.

Mars Missions

Mission Architectures. Nealy et al. (1997) describe a "short-

stay" Mars mission utilizing a nuclear thermal rocket with 30 days on Mars, described as: "... an opposition class mission with a total mission duration of 555 days. The mission begins on January 17, 2014 with an outbound transfer time of 280 days. The inbound leg includes a Venus swing-by." Anderson et al. (2005) also suggest a "short-stay" Mars mission as one option.

However, such a "short-stay" mission is unlikely to be technically feasible or programmatically desirable. All of the relevant design reference missions utilized long stays on Mars to greatly reduce initial mass in LEO, as well as to create a productive exploration mission concept (Hoffman and Kaplan 1997, Drake 1998). For Mars missions, we deal here with a hypothetical conjunction mission with 200-day transits to and from Mars and 560 days on the surface.

Transits to Mars. The 95% CI GCR dose equivalent with 10 g/cm^2 of aluminum shielding during Solar Minimum would amount to about 0.5 cSv/day. For a 200-day transfer to Mars, the total is about 100 cSv that is double the allowable annual dose.

Because crew transits to Mars are likely to require about 200 days in space, the probabilities of encountering major SPEs during Solar Maximum for each leg of the round trip are approximately the same as those given previously for a 180 stay on the Moon. Thus during Solar Maximum, occurrence of a 4X 1972 SPE is about 1.2% probable and occurrence of a 1X 1972 SPE is about 10% probable for each leg. For the round trip the figures would be 2.4% and 20%.

Even with 10 g/cm^2 of aluminum shielding the biological impact of a large SPE would be excessive.

Dose on Mars. In a previous section, we have already emphasized that the effect of the Mars atmosphere is to reduce the GCR dose by 30% at the surface, and taking into account shielding by the planet itself, we may conclude that the 95% CI GCR dose on the surface of Mars was estimated to be roughly 0.21 cSv/day. However, neither aluminum nor regolith shielding is very effective at reducing this. Over the course of a year, the accumulated 95% CI GCR dose is about 77 cSv, which exceeds the annual allowable of 50 cSv. For a 560-day stay on Mars, the cumulative 95% CI dose is about 120 cSv. This would exceed the career allowable dose for most females and younger males.

The effect of the Mars atmosphere on SPE radiation is significant. Simonsen (1997) provided a point estimate of about 10 cSv/event for the 1956 SPE inside a habitat on Mars using regolith shielding. Doses were lower for other major SPEs. Nevertheless, if we multiply the point estimate by ~3.5 to roughly estimate the 95% CI dose, it would exceed the 30-day allowable dose by a moderate amount. The probability of encountering a major SPE in a 560-day surface stay during Solar Maximum would be about 3.4% for occurrence of a 4X 1972 SPE and about 28% probable for occurrence of a 1X 1972 SPE.

Mars Mission Summary. During transit to and from Mars the GCR 95% CI GCR dose equivalent with 10 g/cm^2 of aluminum shielding during Solar Minimum is about double the allowable annual dose for each leg of the trip. Adding more shielding would provide limited improvement. If a major SPE occurred during a transit, the biological consequences would be significant. Tables 13 to 15 provide indications of the biological impact. The probabilities of encountering a large SPE are about 2.4% for a 4X 1972 SPE and about 20% for a 1X 1972 SPE in a round trip of 400 days during Solar Maximum.

On the surface, over the course of a year, the accumulated GCR 95% CI dose is about 77 cSv, which exceeds the annual allowable of 50 cSv. For a 560-day stay on Mars, the cumulative 95% CI dose is about 120 cSv. This would exceed the career allowable dose for most females and younger males. The 95% CI dose from a major SPE would exceed the 30-day allowable dose. The probabilities of encountering a large SPE are about 3.4% for a 4X 1972 SPE and about 28% for a 1X 1972 SPE for 560 days on the surface during Solar Maximum.

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    Wilson1993.pdf NASA lunar mission shield design memo (1993)
    Wilson2001.pdf NASA workshop proceeding paper related to radiation shielding (2001)

Acknowledgement and Disclaimer

National Aeronautics and Space Administration.

Thanks go to the reviewer of this manuscript for valuable suggestions.

List of Acronyms

ALARA	As Low as Reasonably Achievable
BFO	Blood-forming organs
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CEV	Crew Exploration Vehicle
CI	Confidence interval
CNS	Central nervous system
DRM	Design reference mission
ELR	Excess lifetime risk
ESAS	Exploration Systems Architecture Study
EVA	Extra-vehicle activity
GCR	Galactic cosmic radiation
Gy	Gray (unit of absorbed dose ~ Rad)
HDPE	High Density Polyethylene
HZE	high charge and energy for Z > 3 particles
ISS	International Space Station
LEO	Low Earth Orbit
LET	Linear energy transfer
LOC	Loss of Crew
LOM	Loss of Mission
NCRP	National Council on Radiation Protection and Measurement
NHRP	Next Hop Resolution Protocol
NUREG	Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
PDF	Probability distribution function
RBE	Relative biological effectiveness
REID	Risk of exposure-induced death
SEI	Space Exploration Initiative
SPE	Solar particle event
TLI	Trans-lunar injection

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