Interplanetary Human Habitat Passive Radiation Shielding Mass

1. Foreword

This reference is intended for student use in NASA's High School Aerospace Scholars (HAS) educational outreach program. Much of HAS is devoted to student design of a human space flight (HSF) mission into interplanetary space. The problem of shielding a human habitat from radiation in interplanetary space is often chosen by HAS students for detailed study during their 6-day visit to Johnson Space Center (JSC). Multiple means of mitigating harmful effects of this radiation on humans are under study by NASA, such as protective pharmaceuticals or deflective magnetic fields. Until these alternatives are proven effective, however, passive shielding of an interplanetary human habitat is typically the only viable technique available to HAS students. A critical question must then be answered. How much passive shielding mass is sufficient?

The primary intent of this reference is to provide data permitting HAS students to quantify sufficient shielding mass for a human habitat in interplanetary space. In doing so, it will cite other references HAS students may find helpful. It will also provide some background on the interplanetary radiation environment and NASA standards pertaining to acceptable astronaut radiation exposure.

2. Interplanetary Radiation Environment

Any human habitat in interplanetary space is bombarded by potentially lethal ionizing radiation with sufficient energy to break chemical bonds. Without adequate radiation shielding, an exposed human could suffer short-term acute radiation sickness and long-term accelerated aging effects, DNA damage leading to cancer, central nervous system damage, and immune system deterioration [1, p. 7].

Ionizing radiation in interplanetary space arises primarily from two sources. Solar particle events (SPEs) are the first of these. Typically triggered by solar flares, SPEs eject intense bursts of high-energy protons and a few heavier atomic nuclei into interplanetary space over a relatively brief period of hours or days.

The second source is galactic cosmic radiation (GCR), thought to arise from supernovae and other cataclysmic events throughout our galaxy and elsewhere in the universe. High-energy atomic nuclei also comprise GCR, but protons do not predominate as they do in an SPE [1, Figure 2-1]. A significant portion of GCR has atomic number Z as high as 26 (iron, ${}_{26}$Fe). Because ionizing radiation's capacity to break chemical bonds (and thereby damage human tissue) is proportional to Z^2, a single iron nucleus can inflict $26^2 = 676$ times the damage of a single proton [2].

The SPE and GCR components of interplanetary radiation have other differing characteristics. Because SPEs emanate only from the Sun, they have some degree of directionality. Near a large otherwise unshielded body like the Moon or Mars, radiation flux from SPEs can drop dramatically at night. In contrast, GCR is isotropic, originating from all directions. It spirals along our Milky Way galaxy's magnetic field lines continually and flows through interplanetary space in all directions more or less equally. The Sun's magnetic field can divert some of the GCR flux, causing it to vary by a factor of about 2 over the solar activity cycle, whose period is roughly 11 years [1, Box 2-1]. Since SPEs are more likely to occur more frequently and at higher intensity near peak solar activity, GCR tends to dominate interplanetary radiation concerns at other times.

3. Human Radiation Exposure Standards

Earth's atmosphere shields the resident human population from most interplanetary radiation. At zero altitude, atmospheric shielding is equivalent to an area density $\rho_A = 1030$ g/cm^2 [3]. This level of shielding is defined as "RP 100". To restate this condition, humans at sea level enjoy an arbitrary 100% Radiation Protection rating because an air mass of 1030 g is present above every square cm of habitat.

The RP 100 condition is considered arbitrary because it does not shield humans from all interplanetary radiation. The National Council on Radiation Protection and Measurement has computed the background human radiation dose averaged over the entire U.S. population. Interplanetary radiation is responsible for only 0.39 mSv/yr (11%) of the 3.6 mSv/yr total dose, 55% of which arises from exposure to naturally occurring radon gas[1].

Since interplanetary space is a high radiation environment, NASA has adopted the concept of Risk of Exposure-Induced Death (REID) in evaluating the radiation risk of long-duration spaceflight. Death from cancer *directly attributable* to exposure during spaceflight is the single radiation effect NASA associates with REID. The American Cancer Society reports 23% of all deaths in 2004 were due to cancer [1, p. 12]. Thus, the general population on Earth has a 23% likelihood of dying from cancer. The maximum amount of radiation exposure legally permitted for terrestrial workers is specified by the Occupational Safety and Health Administration (OSHA) and is known as a permissible exposure limit (PEL). For NASA astronauts, PELs are specified over various time intervals such that REID is increased no more than 3% above the terrestrial risk for an entire career at a dose confidence level of 95%. The dose confidence level is necessary because a given radiation exposure affects individual astronauts differently, even when they are of the same sex and age. In addition, REID computations are inherently imprecise [1, p. 12].

As a radiation exposure example, consider the relatively low PEL case of a female astronaut taking her first space flight at 30 years old. Although her estimated career PEL is 480 mSv, NASA will not permit her to fly a mission that would bring her predicted career exposure above 120 mSV. With this conservative PEL, there is statistical confidence that 95% of female astronauts beginning their HSF careers at 30 years of age will not incur an additional 3% REID before they are retired [1, Figure 1-3]. Unforeseeable circumstances, such as an intense SPE, may occur during this astronaut's time in space that could bring her career exposure above 120 mSv. In these cases, NASA will curtail activities (such as time outside the shielded habitat) to minimize her radiation dose. If her career dose is approaching 480 mSv, consideration will be

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[1] Reference http://www.umich.edu/~radinfo/introduction/radrus.htm (accessed 15 September 2011).

given to bringing her back to Earth earlier than originally planned. This conservative radiation exposure policy is called "as low as reasonably achievable" (ALARA) by NASA.

It should be noted that interplanetary HSF experience is currently limited to relatively brief Apollo missions lasting less than two weeks, with much of this time spent in close proximity to the Moon's radiation-obstructing mass. The ALARA policy with its conservative PEL values has only seen application to astronauts in low Earth orbit, where the geomagnetic field exerts a substantial shielding influence in addition to Earth's obstructing mass. Best estimates place the blood forming organs (BFO) GCR dose equivalent for an unshielded human in interplanetary space at 1.9 mSv/day [4, Table-1]. Unshielded, our 30-year-old rookie female astronaut could not be sent on a mission planned to spend more than 120/1.9 = 63 days in interplanetary space.

4. Passive Shielding Strategy

Exposure to GCR in interplanetary space has been simulated using various thicknesses of aluminum ($_{13}$Al) to approximate habitat structure and a 10 cm thickness of water to approximate human tissue. As one would expect, exposure decreases as $_{13}$Al thickness increases. Less intuitive is the nature of this variation, which resembles exponential decay. At $_{13}$Al thickness equivalent to $\rho_A = 50$ g/cm^2 or more, GCR exposure fails to fall below a threshold near 1.37 mSv/day [1, Figure 2-15]. This threshold ρ_A is equivalent to an RP of 100*(50/1030) = 5.

The process responsible for this "diminishing returns" result is called spallation. When GCR strikes an atomic nucleus with relatively high Z like $_{13}$Al, spallation causes the nucleus to break up into neutrons, protons, and other nuclei. These spallation products can in turn create additional particle showers, further contributing to the flux of ionizing radiation. Because of this "chain reaction", the intuitive benefit from $\rho_A > 50$ g/cm^2 is counteracted.

Spallation can be substantially reduced with respect to shielding experiments using $_{13}$Al by employing low Z material such as water or hydrogen. In the liquid phase, water and hydrogen also present a much less rigid target than a solid metallic atomic lattice, resulting in further spallation reduction. Estimating a reduced spallation factor attributable to liquid water or hydrogen shielding is beyond the scope of this reference. Nevertheless, use of low Z shielding liquids will certainly serve to increase radiation dose margins for interplanetary HSF in accord with ALARA policy.

The most valuable material in the solar system to HSF may ultimately be water, particularly if it is available for in-situ resource utilization (ISRU) at interplanetary destinations. In addition to its utility as a passive shield against ionizing radiation, water is useful as propellant[2] and as a human consumable. This three-fold utility would lead to a strategy where water obtained from ISRU at one interplanetary location is partially consumed as propellant to depart that location bound for another destination. Post-departure residual water then shields humans from ionizing

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[2] Water may see use as a propellant for nuclear thermal propulsion (NTP), in which it is injected directly into a fission reactor's core. A variant of this technique would see water electrolyzed into hydrogen and oxygen before core injection. Electrolyzed water, subsequently chilled into cryogenic hydrogen and oxygen, can also serve as chemical rocket propellant.

radiation while they consume it for hydration and hygiene purposes during interplanetary transit. Upon arrival at the destination, virtually all residual water is available for propulsive purposes, provided it is promptly replenished by ISRU or the arriving humans are promptly transferred to an adequately shielded and supplied habitat.

5. A Passive Shielding Example And Its Implications

Consider a cylindrical habitat 12.2 m long with a 4.6 m diameter. The cylinder's area is 209.5 m^2. With $\rho_A = 50$ g/cm^2, shielding mass is 104.8 metric tons (mt). This is a substantial fraction of the International Space Station's "assembly complete" mass near 400 mt in 2011. If the cylindrical habitat is occupied in interplanetary space for 16 months = 480 days (typical transits between Earth and Mars with conventional propulsion are 8 months in duration), those occupants will receive a predicted GCR dose of 480*1.37 = 658 mSv. A 30-year-old rookie female astronaut cannot make this round trip, even if she occupies an RP 100 habitat on Mars and never ventures outside to explore. If a 50-year-old female rookie were to make this trip, she too would violate her 95% statistical confidence career PEL of 250 mSv before she reached Mars, and her estimated career dose of 920 mSv would be 72% expended just by her 480 days in interplanetary space [1, Figure 1-3].

There may be other ways to address passive shielding violations of ALARA policy on Mars missions than flying only elderly rookie male astronauts. It may be that such missions justify incurring a REID increase more than 3%. A propulsion breakthrough could substantially shorten interplanetary transit time. Supplemental techniques, such as the previously cited pharmaceuticals, may be used with passive shielding to manage REID increases.

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References

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[3] Vasquez, M. E., "Human Exploration of Phobos and Deimos: Radioprotection Issues". NASA Workshop on the Exploration of Phobos and Deimos, 2007.

[4] Saganti, P. B., Cucinotta, F. A., Wilson, J. W., et al., "Radiation Climate Map for Analyzing Risks to Astronauts on the Mars Surface From Galactic Cosmic Rays", *Space Science Review* 110, pp. 143-156, 2004.[4]

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[3] A free copy of this publication can be downloaded as a PDF file from URL http://www.nap.edu/catalog/12045.html (accessed 12 September 2011).

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[4] A free copy of this publication can be downloaded as a PDF file from URL http://chapters.marssociety.org/winnipeg/radiation/Mars-Flux-Paper.pdf (accessed 16 September 2011)