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Radiation engineering analysis of shielding materials to assess their ability to protect astronauts in deep space from energetic particle radiation

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ABSTRACT

An analysis is performed on four typical materials (aluminum, liquid hydrogen, polyethylene, and water) to assess their impact on the length of time an astronaut can stay in deep space and not exceed a design basis radiation exposure of 150 mSv. A large number of heavy lift launches of pure shielding mass are needed to enable long duration, deep space missions to keep astronauts at or below the exposure value with shielding provided by the vehicle. Therefore, vehicle mass using the assumptions in the paper cannot be the sole shielding mechanism for long duration, deep space missions. As an example, to enable the Mars Design Reference Mission 5.0 with a 400 day transit to and from Mars, not including the 500 day stay on the surface, a minimum of 24 heavy lift launches of polyethylene at 89,375 lbm (40.54 tonnes) each are needed for the 1977 galactic cosmic ray environment. With the assumptions used in this paper, a single heavy lift launch of water or polyethylene can protect astronauts for a 130 day mission before exceeding the exposure value. Liquid hydrogen can only protect the astronauts for 160 days. Even a single launch of pure shielding material cannot protect an astronaut in deep space for more than 180 days using the assumptions adopted in the analysis. It is shown that liquid hydrogen is not the best shielding material for the same mass as polyethylene for missions that last longer than 225 days.

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1. Introduction and analysis overview

A mission to Mars can be defined as a long duration, deep space mission. The Mars Design Reference Mission 5.0 [1] defines long duration as approximately 400 days transit with an approximate 500 day stay on the surface. Since the surface stay can use the Mars atmosphere and planet body as a shield, the transit from and to the earth will be considered deep space. Of course, other missions to near earth objects and the moon can also be considered long duration, deep space missions. An analysis of the shielding needed to protect astronauts during these long duration, deep space missions is described.

The Constellation Program used a design basis exposure of 150 mSv [2] from the Solar Particle Event (SPE) spectrum described in that program to ensure that the career permissible risk of 3% radiation exposure induced death at a 95% confidence level [3] was not reached. While that design basis exposure was intended for the described SPE, it is used here as a reasonable approximation for what a design criterion might be for deep space. In deep space, SPE's are an acute exposure and must be protected against, but are not the subject of this paper. The chronic exposure in deep space is from Galactic Cosmic Rays [4] (GCR). The historical GCR spectrum from the 1977 solar minimum (radiation maximum) is used as the design basis environment to allow comparison to previous analyses.

The OLTARIS [5–7] (On-Line Tool for the Assessment of Radiation In Space) code system is used to generate whole body effective dose equivalent [8] (H_t) in mSv/day for

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various materials with various thicknesses in g/cm^2. For each material, the H_t versus shielding thickness (g/cm^2) is converted to H_t versus total mass in metric tons (tonnes). These data are then converted to H_t versus the number of heavy vehicle lift launches. With these data, the number of days before an exposure value is reached is then determined and converted to launch mass or the number of heavy lift launches.

While the results of this analysis for long duration, deep space missions may seem expected and not surprising, until this simple analysis was performed and understood, surrounding the vehicle with liquid hydrogen was the advice given to would-be spacecraft designers. This analysis refines that initial advice for a shirt sleeve environment inside the vehicle, meaning that all the mass shielding the astronauts have is on the outside of the habitable volume.

The next section establishes the detailed engineering analysis and results. The results are then discussed. The last section states the conclusions.

2. Detailed engineering analysis and results

This engineering analysis starts with determining the H_t with the OLTARIS tool at numerous sphere thicknesses from 0.0001 to 1000 g/cm^2 in four typical materials: aluminum (density = 2.7 g/cm^3), liquid hydrogen (density = 0.07099 g/cm^3), high density polyethylene (density = 0.941 g/cm^3), and water (density = 1 g/cm^3). The historical 1977 solar minimum GCR spectrum was used as the boundary condition.

Liquid hydrogen has always been suggested as the best material to protect astronauts but is a poor structural material even when tanked. Fig. 1 shows the typical plot of dose equivalent [8] in mSv/day (see Appendix A) versus material thickness in g/cm^2 used to support the expectation that hydrogen is the material of choice for radiation protection. This figure shows that liquid hydrogen is a better shield as compared to water and polyethylene. Fig. 1 is the standard view of these materials and their ability to shield astronauts.

Fig. 2 shows the whole body effective dose equivalent in mSv/day (see Appendix B) versus material thickness in g/cm^2 as in Fig. 1. The plots are qualitatively similar, but differ slightly because individual organs are at different places and depths in the body and further they react to radiation in different ways. However, the expectation that hydrogen is the better shielding material can still be supported.

Many proposed long duration, deep space vehicles have been designed around a right circular cylinder; however, to make this calculation simpler, a sphere is used as the vehicle shape to continue the analysis. A particular deep space vehicle design being used in another related project [9] has an inside diameter of 6 m and an inside height of 10 m for a total inside volume of 282.74 m^3. As a point of comparison, the TRANSHab [10], a trans-Mars habitat design, was 8.2 m in diameter and 6.44 m in height for an inside volume of 340.1 m^3 for a crew of 4–6. The optimum volume is about 20 m^3 of habitable volume per crew member [11]. In order to match the reference volume of 282.74 m^3, a spherical vehicle would have an inner radius of 4.072 m.

From this vehicle definition and Fig. 2, the mass of the material (tonnes) in the vehicle shell can be determined and compared to the calculated H_t inside the vehicle. Fig. 3 shows the results. At a total shielding mass of about 500 tonnes, liquid hydrogen (orange line) has the same H_t as water or polyethylene (dark and light green line, respectively). The cross-over is because of the density of liquid hydrogen and how it affects the volume and mass. To show that this is an effect of the material density and not of the physics behind the calculation of H_t, consider the following example. If the density of liquid hydrogen is increased to the same order of magnitude as water or polyethylene, an unobtainable 1 g/cm^3, then this cross-over does not occur until 5000 tonnes and meets the expectations as shown by Figs. 1 and 2. Also in Fig. 3, the black lines denote the mass of a number of heavy lift launches at 89,375 lbm per launch (40.54 tonnes per launch). The 89,375 lbm (40.54 tonnes) mass is derived from the initial mass to low Earth orbit value for the Space Launch System of 286,000 lbm [12] (129.73 tonnes) with a

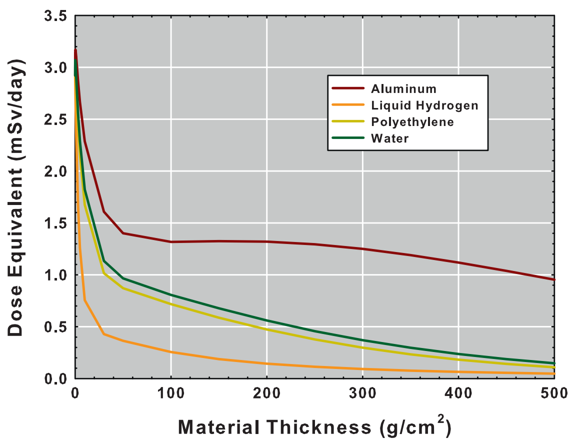

Fig. 1. Standard dose equivalent in mSv/day to the thickness of a material in g/cm^2.

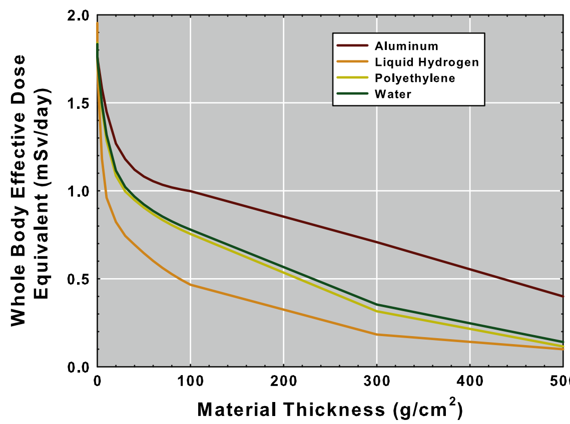

Fig. 2. Standard whole body effective dose equivalent in mSv/day to the thickness of a material in g/cm^2.

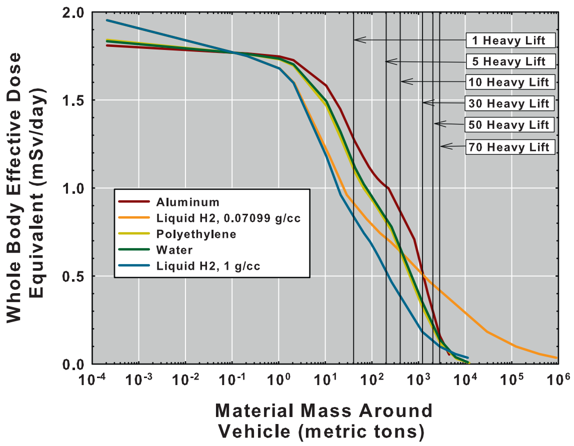

Fig. 3. Whole body effective dose equivalent in mSv/day for a shielding material in a spherical vehicle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

gear ratio of 3.20 [13] for trans-Mars injection (TMI).

Fig. 4 shows a geometrical representation of the shielding configuration. In a slab, the surface area at the habitat-shield boundary is the same as the surface area at the shield-space boundary and all the mass of the shield is utilized. However, since the vehicle is spherical, the surface area changes as the thickness of the shield changes. Therefore, there appears to be extra mass as denoted in red in Fig. 4. As the density of the material decreases, the thickness increases non-linearly and so does the mass needed to create the spherical shell around the habitat.

From another point of view, the density of a material shifts what part of the independent axis or material thickness in g/cm^2 in Figs. 1 and 2 is being used for a given depth in meters to determine the H_t. That given depth leads directly to volume which when multiplied by the density gives mass. For low density materials, the thickness in g/cm^2 is smaller at a given volume of the material and therefore, the H_t in mSv/day is larger. As shown in Fig. 5, for nominal density liquid hydrogen, the thickness at a depth of 70 cm is only 5 g/cm^2. For water, the thickness at 70 cm is 70 g/cm^2. The H_t for liquid hydrogen at 5 g/cm^2 is 1.18 mSv/day and for water at 70 g/cm^2 is 0.855 mSv/day. Therefore, for the same volume, because of the density difference, water has a lower H_t than liquid hydrogen.

The exposure rates in Fig. 3 can be used to calculate the number of days before the design basis exposure of 150 mSv is reached. A mission designer usually has knowledge of the mission duration due to constraints that cannot be overcome with current technologies (e.g. orbital dynamics and propulsion systems). The designer must then determine the mass required to meet crew exposure limits over the specified mission duration. Therefore, Fig. 6 plots days to the exposure of 150 mSv as the independent variable to the number of heavy lift launches needed to get the required shielding mass to TMI. Again, liquid hydrogen at 1 g/cm^3 (blue line) is included in the figure. It is evident that liquid hydrogen at nominal density (orange line) is not the best shielding material if the mission is longer than 225 days, but water and polyethylene are better shielding materials for longer missions. However, if the density of liquid hydrogen is increased (blue line), it becomes a better shield material than water or polyethylene to greater than 1200 days. Fig. 7 shows in detail the lower left corner of Fig. 6 where the liquid hydrogen cross-over occurs and the details of the small launch numbers are expanded.

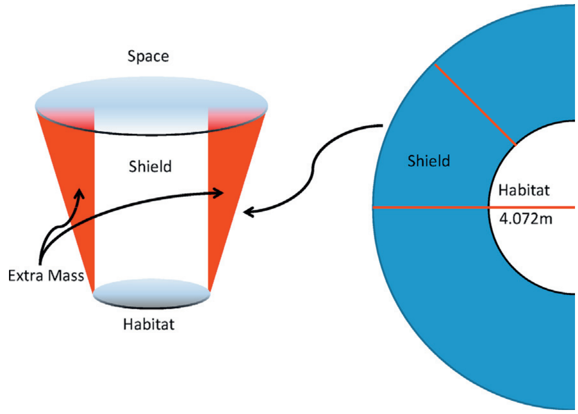

Fig. 4. Geometry of vehicle showing extra mass carried by the geometry. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

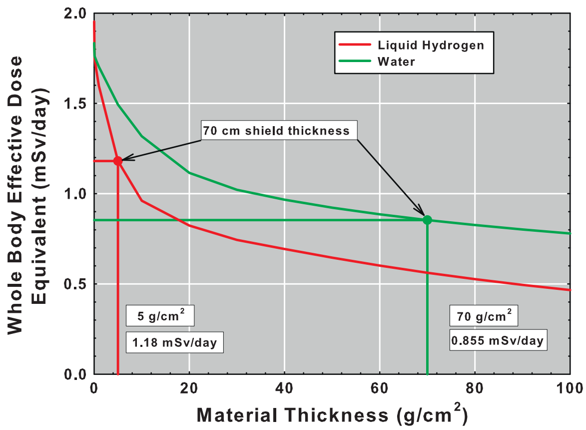

Fig. 5. Example of liquid hydrogen and water from Fig. 2 in a spherical shield at a constant thickness of 70 cm.

3. Discussion of results

While these results are expected and not surprising from an engineering point of view, they are not intuitive from previous analyses driven by Figs. 1 and 2. At large depths, liquid hydrogen always protects better than any other material. However, when placed into an engineering analysis including geometry and density, then a different picture is exposed as shown in Figs. 6 and 7.

The primary finding of this analysis is that for shielding to be provided solely by mass around a deep space vehicle, a large number of heavy lift launches are needed to meet the exposure value, an H_t of 150 mSv.

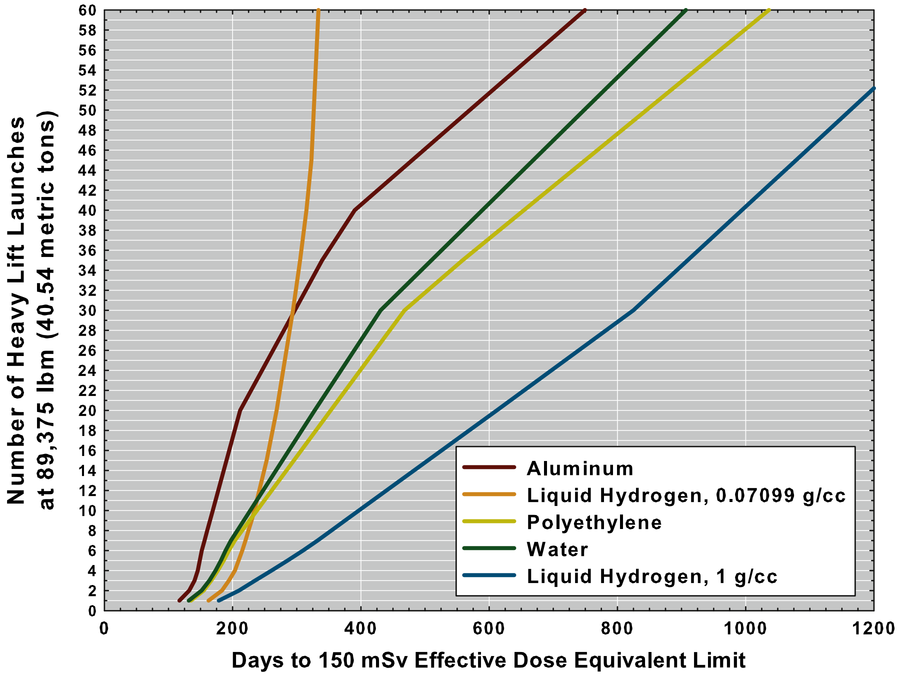

Fig. 6. The number of days to the 150 mSv exposure per mission for various shielding materials. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

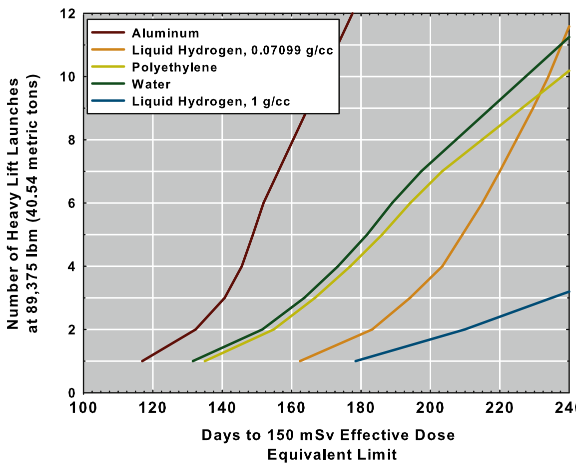

Fig. 7. The number of days to the 150 mSv exposure per mission for various shielding materials (inset).

The latest proposed Mars mission, Mars Design Reference Architecture 5.0 [1], has a 200 day transit to Mars and a 200 day transit from Mars. It also has a 500 day stay on the surface. The surface stay is not addressed by this analysis; however, for the 400 days in deep space, Fig. 6 indicates that 24 heavy lift launches are needed of pure polyethylene to enable this transit. The figure also shows that nominal density liquid hydrogen would not provide sufficient shielding to satisfy the design basis exposure up to 60 launches. However, if presently unobtainable 1 g/cm^3 liquid hydrogen could be used, then only 10 launches would be needed to adequately meet the expectations derived from an analysis of Fig. 1.

The long held belief that liquid hydrogen is the best shielding material needs to be qualified. For missions that last longer than 225 days, the same mass of polyethylene or water allow more days for a mission than liquid hydrogen. This belief may have been perpetuated by thinking of liquid hydrogen as having a density near to that of water, whereas its density, in actuality, is well below that of water.

One of the major findings of this study is that for a single launch of just shielding materials, if water or polyethylene is used, the mission length is 130 days. Aluminum reduces the mission duration. Nominal density liquid hydrogen only increases the mission duration to approximately 160 days. Even the unobtainable density liquid hydrogen increases the mission duration to only 175 days. Therefore, even a single launch of pure shielding material cannot support stays in space over 180 days with the assumptions used in this paper.

What has not been included in this analysis is the packaging of the material inside a rocket fairing and a planetary stay under an atmosphere. A follow on paper will include the volume of the mass and will modify the number of launches based on mass and volume. The mass of cryo-cooling equipment and tank materials for liquid hydrogen may also be included.

The other major assumptions used by this analysis will also be relaxed. The first assumption relaxed is the mass and H_t being calculated with a sphere by actually using a ray trace of a right circular cylinder (RCC) vehicle in OLTARIS to calculate H_t and the formula for a RCC to calculate the mass shell. The second assumption relaxed is that the exposure is constant over the mission duration by performing the analysis at a historical solar maximum and solar minimum to get a range instead of a single value. The last assumption that will be relaxed is that the mass is concentrated at the vehicle shell. There are many ways to distribute the mass within the vehicle from personal shielding to heavily shielding areas where the crew spends most of its time.

There are many infrastructure launches not included in this analysis. Launches like tugs to push the fully configured habitat from low earth orbit to high earth orbit for the TMI burn. Launches to place radiation and communication satellites to allow full coverage of the mission to solar events and continuous communications. To get astronauts into deep space is a complex technical issue. Radiation issues are just one component of the mission.

Ultimately, an engineering analysis that includes the density of the materials being used with a vehicle geometry is needed to fully understand the characteristics that a long duration, deep space mission can have. With no regulatory based design basis defined for an exposure limit, the absolute numbers reported here will vary linearly with this value.

4. Conclusion and future work

The analysis described in this paper shows that vehicle mass cannot be the sole shielding mechanism for long duration, deep space missions. Single, heavy lift launches of any shielding material with the assumptions used in this paper will not support astronauts for more than 180 days. A 400 day transit mission to Mars, without including the surface stay, would take 24 heavy lift launches of polyethylene to meet the assumed design basis exposure. For missions longer than 225 days, polyethylene is a better material for shielding than liquid hydrogen.

There are numerous ways to increase the number of days an astronaut can stay in deep space. The assumptions in this analysis will be relaxed in a future analysis. Also, the NASA Office of the Chief Technologist has a roadmap, Technology Area 06 [14], that suggests and is actively researching design and operational improvements.

Appendix A. Dose equivalent defined

While dose gives the energy deposited by a particle in a material, it does not estimate the probability of stochastic effects in humans such as cancer mortality. For the “complex mixture of high- and low-LET radiation experienced in LEO” [15], the National Council on Radiation Protection and Measurement (NCRP) endorses the use of dose equivalent calculated with the ICRP-60 [16] quality factor, Q, for this purpose [8,15,17]. As yet, the NCRP has not made a recommendation for space environments beyond LEO [17], but this paper has adopted the approach of using dose equivalent for beyond LEO vehicles. Dose equivalent is defined as

$$H = \sum_j H_j,$$

where

$$H_j = \int_0^\infty dE\, Q(S_j(E)) S_j(E) \phi_j(E) + h^\star(E).$$

The quality factor Q is defined as [16]

$$Q(S_j(E)) = \begin{cases} 1, & 0 < S_j(E) \le 10 \\ 0.32 S_j(E) - 2.2, & 10 < S_j(E) \le 100 \\ \dfrac{300}{\sqrt{S_j(E)}}, & 100 > S_j(E) \end{cases}$$

where $S_j(E)$ is the stopping power of a charged particle j at energy E in the material, tissue, or organ of interest in units of keV/μm. The stopping power of neutral particles in any material is zero; therefore, the integral term is zero. Since heavy target fragments and recoil nuclei are not transported, their dose equivalent is added by the $h^\star(E)$ function [18].

Appendix B. Whole body effective dose equivalent defined

As is recommended in NCRP-132 and NCRP-142, effective dose equivalent is calculated by first determining the averaged dose equivalent for the organs and tissues listed in Table B1. The remainder organs are listed in NCRP-132 as adrenals, brain, small intestine, large intestine, kidneys, muscle, pancreas, spleen, thymus, and uterus. A weighted average of all these organs or tissues dose equivalent values is determined by

$$H_t = \sum_o w_o \overline{H}_o, \quad \text{(B.1)}$$

where w_o are the NCRP-132 tissue weighting factors in Table B1 and $\overline{H}_o$ are the organ or tissue averaged dose equivalents as calculated by OLTARIS.

Organ or tissue averaged dose equivalent is calculated by first calculating the dose equivalent at a large enough number of target points in the organ or tissue to accurately characterize that organ or tissue and then averaging these point values. Currently in OLTARIS, the user can select one of the four human body models (CAM [19], CAF [20,21], MAX [22], or FAX [23]) for these calculations. For this calculation, the CAF phantom was used.

Table B1
NCRP 132 organs and their weights.

Tissue Weights	Tissue types
0.01	Bone surface
	Skin
0.05	Bladder
	Breast
	Liver
	Esophagus
	Thyroid
	Remainder
0.12	Bone marrow
	Colon
	Lung
	Stomach
0.20	Gonads

There are a few body model specific details that should be noted. First, there are ten remainder organs for the females, but only nine for the males. For this reason, the tissue weighting factor, w_o, for each of the remainder organs is 0.05/10 for females and 0.05/9 for males. Second, in the CAF and CAM models, the colon, large intestine, and small intestine are treated as one organ. This organ labeled intestine is therefore assigned a tissue weighting factor equivalent to the sum of the tissue weighting factor specified for colon, 0.12, and the tissue weighting factors for two remainder organs. Thus the intestine weighting factor is $0.12+2\times 0.05/10$ for CAF and $0.12+2\times 0.05/9$ for CAM. Similarly, the colon and the large intestine are treated as one organ and labeled "colon" in the FAX and MAX models, but the small intestine is treated as a separate organ in these models. The weighting factor for colon is therefore $0.12+0.05/10$ in FAX and $0.12+0.05/9$ in MAX.

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