A Launch Requirements Trade Study for Active Space Radiation Shielding for Long Duration Human Missions

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Acronyms

ALARA	As Low As Reasonably Achievable
EVA	Extra-Vehicular Activity
GCR	Galactic Cosmic Rays
IMLEO	Initial Mass to Low Earth Orbit
NIAC	NASA Innovative Advanced Concepts
SLS	Space Launch System
SPE	Solar Proton Events
TMI	Trans-Mars Injection
YBCO	Yttrium-Barium-Copper-Oxide superconductor

Abstract

A trade study for an active shielding concept based on magnetic fields in a solenoid configuration versus mass based shielding was developed. Monte Carlo simulations were used to estimate the radiation exposure for two values of the magnetic field strength and the mass of the magnetic shield configuration. For each field strength, results were reported for the magnetic region shielding (end caps ignored) and total region shielding (end caps included but no magnetic field protection) configurations. A value of 15 cSv was chosen to be the maximum exposure for an astronaut. The radiation dose estimate over the total shield region configuration cannot be used at this time without a better understanding of the material and mass present in the end cap regions through a detailed vehicle design. The magnetic shield region configuration, assuming the end cap regions contribute zero exposure, can be launched on a single Space Launch System rocket and up to a two year mission can be supported. The magnetic shield region configuration results in two versus nine launches for a comparable mass based shielding configuration. The active shielding approach is clearly more mass efficient because of the reduced number of launches than the mass based shielding for long duration missions. Efforts are underway to better understand the engineering integration complexities and resolutions such as thermal issues and superconductor materials; therefore, due to the limited number of simulations, all results in this paper have large uncertainties and are unquantifiable, especially as the configuration trades deviate from the two calculated configurations; however, it is clear that the reduction in launches is significant for the active shielding concept.

1   Introduction and Background

Protecting astronauts from space radiation is the main obstacle for long duration missions. In general, time, distance, and shielding augmented by the ALARA (As Low As Reasonably Achievable) concept are the three parameters that can be used to minimize radiation exposure. On Earth, all three parameters can be used as there are usually no limits to any of these items. However, in space, time isn't a variable as the astronauts spend all of their time in the radiation field; therefore, the mission duration is the only time available. With the space radiation source being essentially omni-directional on all boundary surfaces of the spacecraft, the distance between the source and the astronauts becomes immaterial which leaves shielding and ALARA as the only controllable constraints. The design of the spacecraft and the concept of operations to utilize the shielding usually meet ALARA requirements. For this report, the concept of operations will not be addressed in detail.

To minimize radiation exposure through shielding, three items can be engineered: the human, the spacecraft, and/or the environment on the habitat surface. This paper will address engineering the environment at the habitat surface. To determine what kind of shielding is appropriate for a space mission depends on the type of radiation the source contains. The types of high energy, charged particle radiation in space are two fold: Galactic Cosmic Rays[1,2] (GCR) as shown in Figures 1 and 2, and Solar Proton Events[3-7] (SPE) with some historic examples shown in Figure 3.

The methods that can be used for shielding are numerous. The state of the art is mass based shielding. Other technologically available methods are based on electro-magnetic fields

to bend the charged particles away from the habitable volume of the vehicle. The method on which this report concentrates is based on a series of magnetic fields in a solenoid configuration as designed and analyzed in the completed NIAC (NASA Innovative Advanced Concepts) Phase I Final Report[8] entitled "MAARSS: Magnet Architectures and Active Radiation Shielding Study." Figure 4 shows the vehicle configuration used in the NIAC study. This report is referred to as the *NIAC report*.

1.1 State of the Art Mass Analysis

Mass based shielding requirements need to be determined for GCR to protect astronauts. These results can then be compared to the trade study of active shielding concepts presented in this report. A human mission to Mars[9] can be used to define the mission parameters of this analysis. The mission to Mars spends about 400 days in deep space where the major radiation source is GCR.

An analysis to shield a GCR source using only mass has been conducted.[10,11] This analysis is summarized here. Previous analyses on how to protect astronauts from GCR used end-points analogous to those shown in Figure 5, which describes dose equivalent[12] versus depth in several relevant space materials, or Figure 6, which shows whole body effective dose equivalent[13] versus depth in those same materials. As shown for either end-point, liquid hydrogen should be the best shielding material; however, if a vehicle designer desires to use the best shielding materials, then a specific vehicle needs to be included in the analysis and then the density of the materials becomes important.

The Space Launch System[14] (SLS) has a lifting capacity of 286,000 lbm (129.73 metric tons) to low Earth orbit (Initial Mass to Low Earth Orbit - IMLEO). Assuming a gear ratio or mass change factor of 3.2 from low Earth orbit to trans-Mars injection[15] (TMI), then the mass that a single SLS can inject towards Mars is 89,375 lbm (40.54 metric tons) which is a heavy lift launch.

A generic sphere model was used with the shielding on the outside of the sphere to maintain a constant internal volume. The sphere's radius was chosen to match the NIAC report vehicle habitable volume of 282.74 m^3 (a 6 m diameter by 10 m high right circular cylinder) which gives an effective radius of 4.072 m. Figure 7 shows that liquid hydrogen may not be the best shielding material as the mass grows faster than the mass of polyethylene or water for the same whole body effective dose equivalent. This figure also shows liquid hydrogen at the same density as water, not its nominal density, and it shows the expected trend of liquid hydrogen from Figures 5 and 6. However, it is not possible to have the density of liquid hydrogen 1 g/cm^2. Also in Figure 7 is the mass in the number of heavy lift launches at 89,375 lbm (40.54 metric tons) per launch.

A mission designer is saddled with mission parameters that are hard to change such as mission duration. The next step in the analysis was to apply the data in Figure 7 to the number of days in a mission before some radiation exposure "limit" is reached. As described in detail in the original mass based analysis,[10,11] a GCR exposure of 15 cSv was used in the analysis. Figure 8 shows the number of heavy lift and IMLEO launches versus the number of days to reach the 15 cSv exposure.

As stated earlier, this type of analysis shows that polyethylene becomes a better shielding material for missions longer than 225 days than liquid hydrogen. For a Mars mission at 400

days, 24 launches of polyethylene, the best shielding material for that mission duration, are needed for TMI or 7.5 IMLEO launches.

1.2   NIAC Phase I Report Analysis Overview

At the start of the Phase I NIAC project, many technology reviews were studied looking at non-mass based shielding. One in particular was the ESA (European Space Agency) study on this type of active shielding.[16,17] The review of previous work outlined in the NIAC report concluded that electro-magnetic based shielding technologies have problems. Most of these problems involve deficiencies with the science or currently insurmountable engineering issues. For example, electrostatic shielding will work if the large voltages can be isolated from the spacecraft inside the field and can be kept from leaking into space as space is not a perfect vacuum. Currently, there are no sound engineering methods to solve these issues.

One plausible active shielding concept that has been enabled with the recent advances in superconducting technologies is magnetic shielding. The Earth's magnetic field, along with approximately 1000 g/cm^2 of atmosphere at sea level, is what protects humans on the Earth's surface. There are engineering integration and concept of operations questions, among others, that must be addressed in order to make active magnetic shielding available to spacecraft designers.

The NIAC report contains details on active shielding radiation protection. The magnet configuration shown in Figure 4 is six, 1 Tesla coils, 8 meters in diameter and produces a maximum integrated magnetic field strength of 8 Tesla-meter (Tm). The average integrated magnetic field strength is about 6.3 Tm around the entire habitat. The 8 Tm configuration was analyzed in depth in the NIAC report. This trade study uses the NIAC report configuration and analyzes a second configuration that increases the mass of and field for the coils to handle 2.5 Tesla, but keeps the diameter the same. This 20 Tm maximum integrated magnetic field strength configuration was analyzed for its radiation properties in the same manner as the 8 Tm configuration.

The NIAC report radiation results consisted of two analyses. The first is the radiation exposure that includes the magnetic field, the magnet's coils and structure, and habitat but not the end-caps. This configuration will be referred to as *magnetic region shielding*. The second is the radiation exposure that includes the magnetic field, the magnetic coils and structure, habitat, and the habitat end caps where no electromagnetic coil is available for shielding. This configuration will be referred to as *total region shielding*. The nominal mass thickness of the habitat and its end caps are 1.8 cm of aluminum (4.86 g/cm^2).

The results of these analyses are shown in Table 1. These data are used in this report to generate a trade study of maximum integrated magnetic field strength (Tm) in Tm versus body dose (BD) in cSv/year and mass (M) in metric tons.

To complete the analysis of the NIAC report vehicle configuration with active shielding for use in deep space, numerous engineering issues were addressed in the NIAC report. The important issues were the choice and configuration of the magnets. The high temperature superconductor YBCO (Yttrium-Barium-Copper-Oxide) was chosen to be the coil conductor. The initial current of 40 kA is to be supplied by a flux pump to allow low amperage current over time (on the order of a couple of 100 hours) to fully charge the coils. Two types of

thermal issues were addressed: keeping the coils cold so they can superconduct and keeping the thermal heat from the environment and the habitat from heating the coils.

2 Trade Study Analysis and Discussion

The objective of this trade study is to determine what magnetic field configuration is needed to meet a total mission exposure value of 15 cSv. The resultant magnetic field configuration has an associated IMLEO launch mass and is compared to the current heavy lift launch capability with the SLS. These values are then compared to a astronaut protection system based on mass only. However, as a trade study, other magnetic configurations can be analyzed and compared to mass-based systems. It must be noted, that the farther away a magnetic field configuration is from the two configurations analyzed, the larger the uncertainty is and that uncertainty in unquantifiable.

In the NIAC report analysis, the response function was based on a cylindrical water phantom with the body dose calculated as a dose equivalent from the entire dose deposited in the phantom or Body Dose in Table 1. In the state of the art mass analysis from Section 1.1, the whole body effective dose equivalent was used as the response function where a human phantom is analyzed and a weighted sum of dose equivalent over each organ is employed.[13] These response functions will be considered equivalent for this analysis. Therefore, the 15 cSv value used in the state of the art mass analysis in Section 1.1 is applied to the Body Dose column values from Table 1.

In Table 1, the two magnetic configurations can be used with a linear fit to generate these interpolation/extrapolation functions for the total and magnetic regions and the mass as follows:

Total Region Shielding

$$BD = -0.35 \times IMF + 39.1 \tag{1}$$

Magnetic Region Shielding

$$BD = -0.64167 \times IMF + 28.33333 \tag{2}$$

Mass

$$M = 3 \times IMF + 12 \tag{3}$$

where BD is the body dose in cSv, IMF is the maximum integrated magnetic field strength in Tm, and M is the estimated configuration mass to IMELO in metric tons. It is very important to realize that the linear scalability of this type of system especially for mass is unknown at this time. Therefore, large uncertainties exist the farther away any prediction is from the 8 and 20 Tm values with their mass values.

Figure 9 shows these interpolation/extrapolation functions versus the maximum integrated field strength. The independent axis in the figure is the integrated magnetic field strength in Tm or IMF in Equations 1 through 3. The left hand dependent axis of the figure is the body dose in cSv/year and is the axis for Equations 1 (blue line) and 2 (red line). The right hand dependent axis of the figure is the estimated configuration mass to IMLEO

in metric tons and is the axis for Equation 3 (pink line). The two sets of points represent the data in Table 1. The green points are for the 8 Tm configuration and the cyan points are for the 20 Tm configuration.

Figure 10 shows how to use the active shield trade study, Figure 9, to determine the requirements of a 1 year stay in space. First, the maximum astronaut body dose is set at 15 cSv (1 year times 15 cSv/year). The horizontal black line labeled "1 Year" is drawn to both configurations of the NIAC report vehicle: magnetic region shielding (red line) and total region shielding (blue line). For the magnetic region shielding (red line), the magnetic field configuration is 20.8 Tm. For the total region shielding (blue line), the configuration is 69.9 Tm. A vertical black line is drawn from the intersection of the "1 Year" line and the magnetic region shielding (red line) to the estimated configuration mass to IMLEO (pink line) and that associated value is 74 mt. For the total region shielding, a similar process is used and the estimated configuration mass to IMLEO value is 219 mt.

Figure 9 can be used to determine the properties of any variable in the trade study. Two other examples given here are a 2 year stay in space (Figure 11) and for the maximum SLS carrying capacity (Figure 12).

The mass analysis in Section 1.1 determined that the number of TMI launches direct to Mars is 24 and the number of IMLEO launches for a Mars transit is 7.5 just to get the needed mass around the habitat. Neither of these launch estimates include astronauts, tugs if needed, and other logistical items. For the NIAC report analysis discussed in Section 1.2, multiple launches were also assumed. The first launch is to pack all 6 magnets for eventual deployment in low or high Earth orbit. The second launch is the habitat and compensating coil. Example common launches for both missions would be delivery of the astronauts, logistics supplies/modules, potential spiral or chemical tug/bus, and interplanetary propulsion capabilities. If a surface landing is desired, deorbit with the lander as well as Mars surface and ascent infrastructure would be required. However, for the analysis of mass based and active shielding, no surface stay on Mars is assumed.

The total region shielding (the blue line in Figure 9) requires that large magnetic fields are needed to shield astronauts to the exposure value. The NIAC report configuration has 1 Tesla magnets in an 8 m solenoid configuration. For comparison, the state of the art superconducting magnets in the Large Hadron Collider uses 8 Tesla magnets and requires large amounts of mass to support the entire structure and support equipment. If that strength of magnet is used for the NIAC report vehicle in an 8 m solenoid configuration, then the integrated strength is 64 Tm. From Figure 9, the total region shielding (blue line) will not support a 1 year mission. The structure needed to support 8 Tesla coils on the NIAC report vehicle would be prohibitive in the solenoid configuration from a materials point of view due to the large magnetic generated forces for which compensation is needed. The equivalent of the 64 Tm configuration just described is 64 m diameter coils at 1 Tesla. Trying to get this system packaged, launched, deployed, and operational is a more complex engineering problem than the current configuration, but is still a solvable engineering problem. The other solution is to increase the mass for the end caps which will lower the exposure. In the planned NIAC Phase II work, the end-cap mass will be investigated and analyzed in detail.

The magnetic region shielding (the red line in Figure 9) shows that smaller fields are needed to shield astronauts to the exposure value as compared to the total region shielding. The one year duration mission in Figure 10 at 20.78 Tm is just a slight extrapolation to

the supported analysis at 20 Tm, so the uncertainty is low for this configuration. The IMLEO mass at 74.34 metric tons can be easily launched with the SLS. Even the 2 year mission in Figure 11 can be launched with the SLS, but the IMLEO mass uncertainty is large. Ultimately however, these IMLEO mass values assume that the ends caps have no contribution to the body dose. As shown in Section 1.1, the end caps must contribute to the body dose. Therefore, more work is needed to define the end caps and their radiation properties that will add to the magnetic region shielding value and then a figure like Figure 9 can be used to predict IMLEO launch mass. Also, the farther these extrapolations are from 20 Tm, the greater the uncertainty is for the IMLEO mass increases.

In summary, Table 2 shows the number of launches for the mass based mission, 8.5 launches, and the magnetic region shielding mission, 2 launches. The 400 day Mars mission is the reference used in the table. The magnetic region shielding value for 400 days resulted in an integrated field strength of 21.89 Tm which gives a mass of 77.67 metric tons or 1 SLS launch to IMLEO with 40% mass margin. There is a stark difference in the number of launches needed by each shielding type and while the absolute number of launches have large uncertainties, the launch number difference is the important element. Both mass based and solenoid based shielding technologies still have engineering and operational problems left to be solved, but they are solvable with research and testing.

3   Conclusion

A trade study space has been created by extrapolating two configurations of solenoid magnetic fields: 8 Tm and 20 Tm and their estimated mass to IMLEO (mt). An active space radiation shield based on the solenoid magnet configuration from this trade study has merit in the comparison to mass based shielding. The NIAC report discusses the engineering details of packaging for launch, deployment, and operation to include magnet quench for this configuration. The trade study developed here shows that, if the NIAC report engineering details can be validated as physical and built in prototype, then the solenoid based system at two IMLEO launches of the SLS is a better trade than nine launches of polyethylene shielding for a deep space mission that lasts 400 days – a mission to and from Mars – to meet an exposure value of 15 cSv.

The trade study developed here is a two point trade study. It must be emphasized that uncertainties increase as the magnetic field strength deviates from the 8 Tm and the 20 Tm points used to generate the trade study. The linear approximation used to generate Figure 9 must be vetted. An effort is underway at NASA Langley to use a hybrid analytical/deterministic method to reduce that uncertainty along with Monte Carlo results for verification. The NIAC Phase II study is further defining the details needed to support the packaging, deployment, and operation of an active shielding system. However, it is clear that the reduction in launches is significant for the active shielding concept.

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Table 1: Magnet configuration, radiation protection, and mass data without Monte Carlo statistical errors.

Maximum Field Strength (Tm)	Body Dose (cSv)		Mass (metric tons)
	Magnetic Region	Total Region	
8	23.2	36.3	36
20	15.5	32.1	72

Table 2: Number of launches for the active technology at 21.89 Tm and 77.67 metric tons compared to the number of launches for the mass only technology analyses for a 400 day transit to Mars.

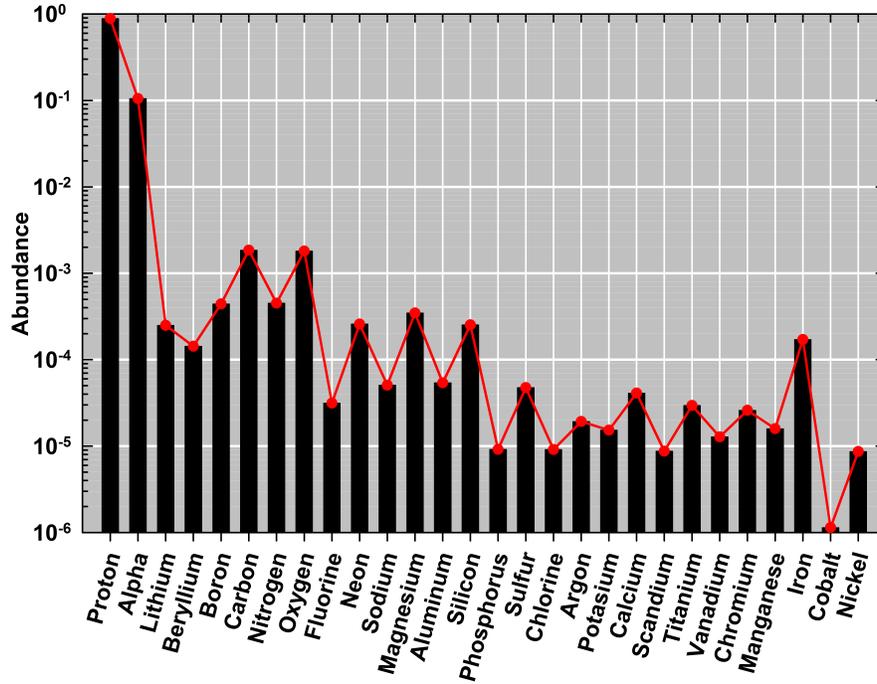| Launch Item	Magnetic Region (Number of Launches)	IMLEO Mass (Number of Launches)
Shielding	1	7.5
Habitat	1	1
Total	2	8.5

Figure 1: Abundance of the smallest 28 elements in the Galactic Cosmic Ray particle spectrum.
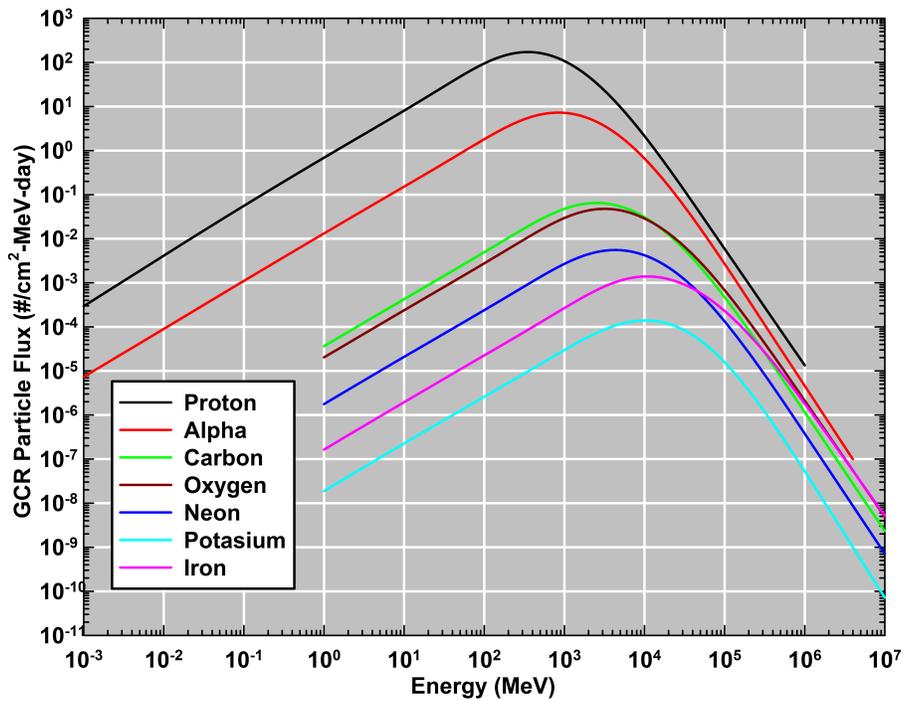

Figure 2: Flux of a select few elements in the Galactic Cosmic Ray particle spectrum.
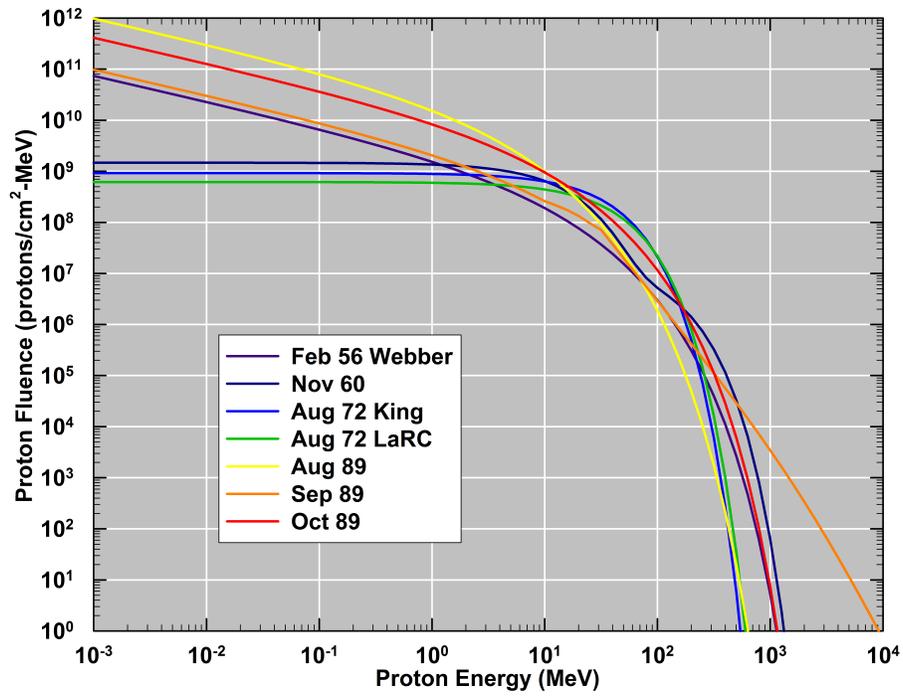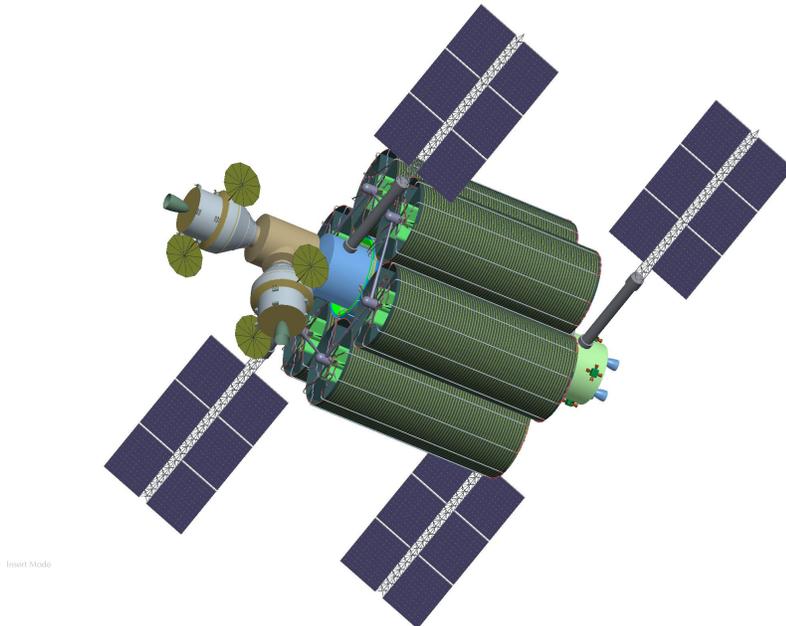
Figure 3: Some historic Solar Proton Events fits.

Figure 4: The NIAC report final vehicle configuration with six coils at one Tesla and eight meters in diameter with a compensating coil around the habitat (not visible) to block any magnetic field that leaks into the habitat.
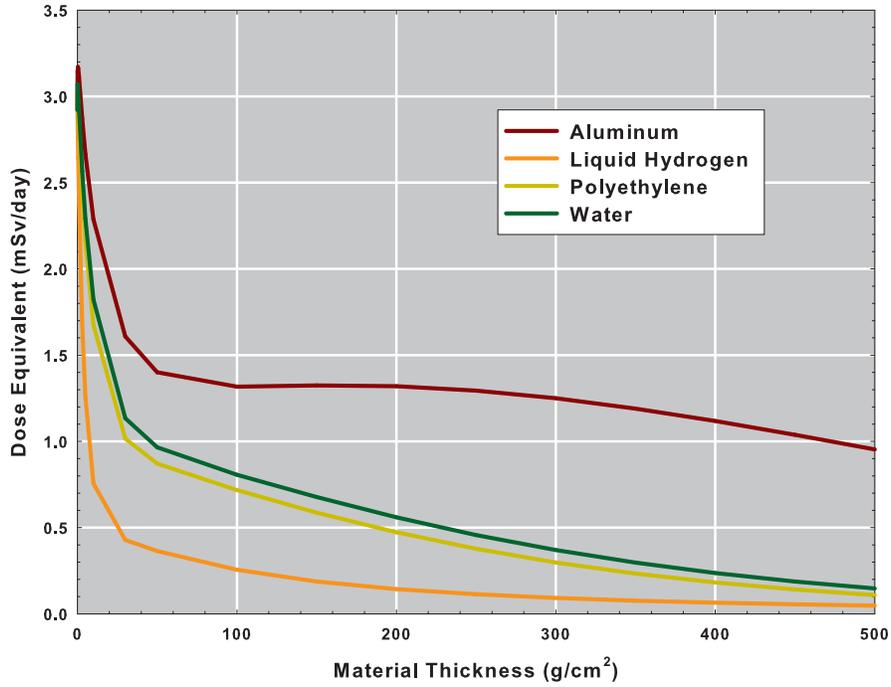
Figure 5: Dose equivalent rate versus depth for four major aerospace materials: liquid hydrogen, polyethylene, water, and aluminum.
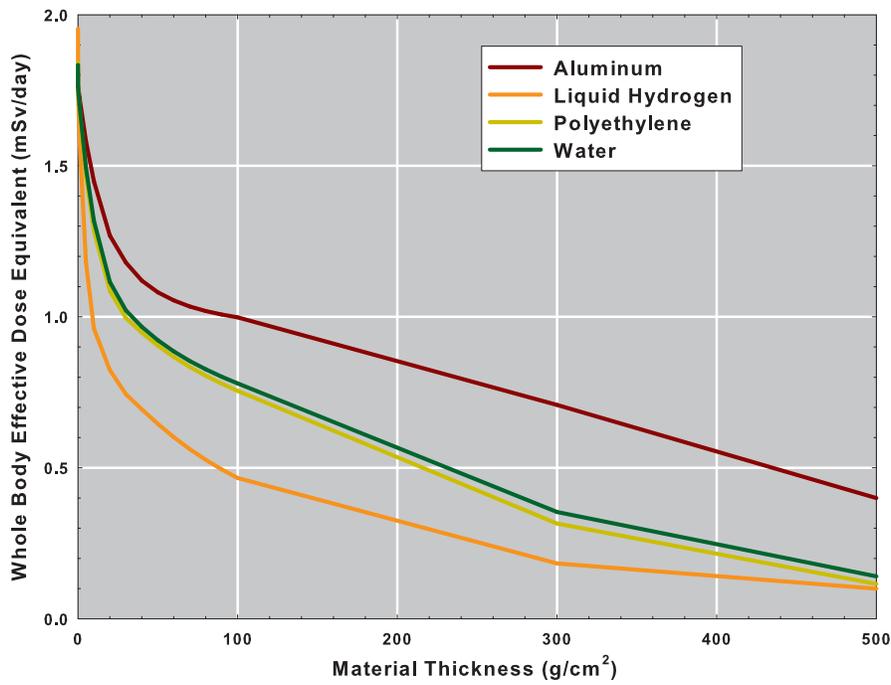

Figure 6: Whole body effective dose equivalent rate versus depth for four major aerospace materials: liquid hydrogen, polyethylene, water, and aluminum.
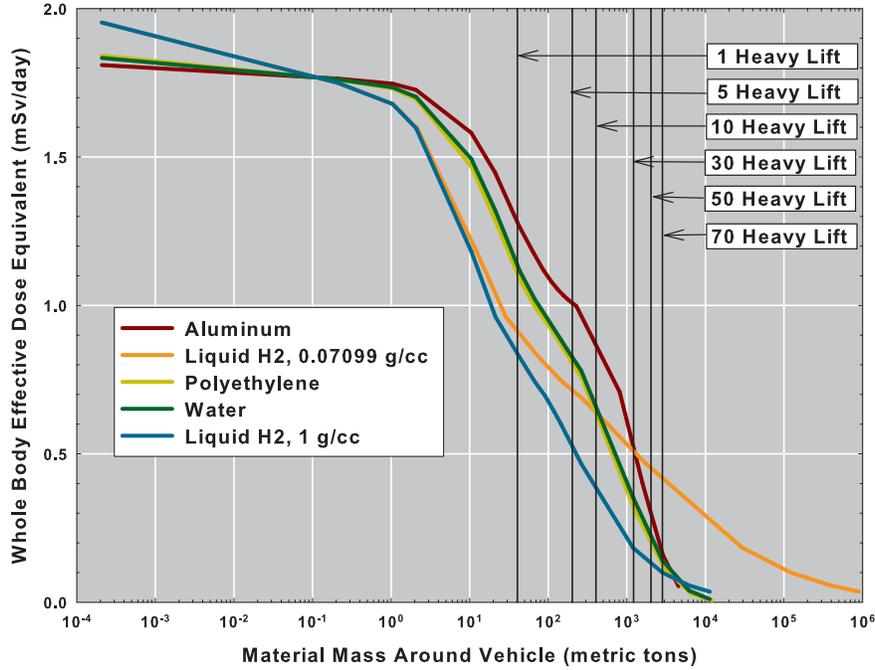
Figure 7: Whole body effective dose equivalent rate versus mass for four major aerospace materials: liquid hydrogen, polyethylene, water, and aluminum.
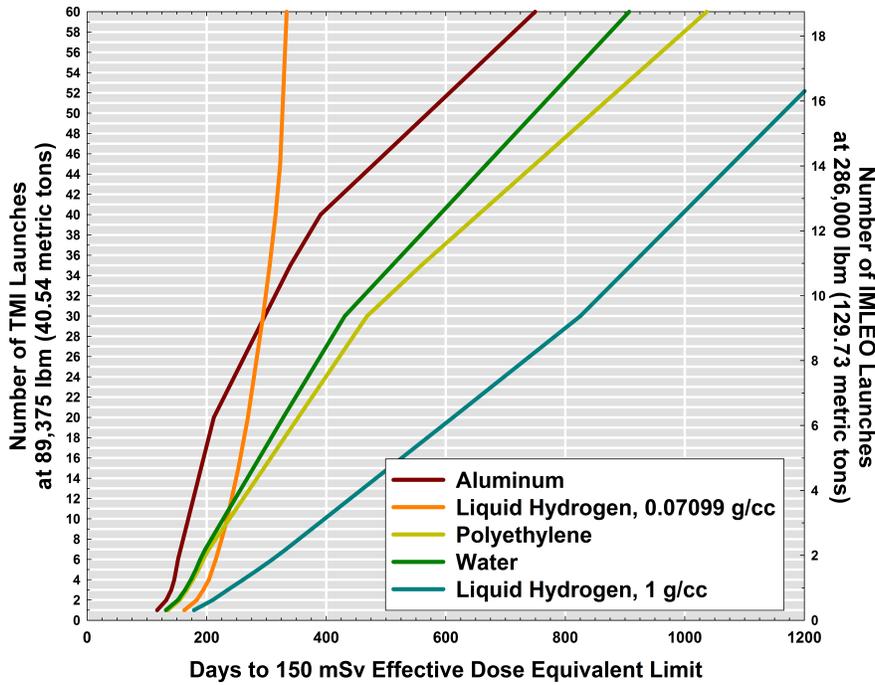

Figure 8: Number of SLS TMI and IMLEO launches versus days to 15 cSv (150 mSv) value for four major aerospace materials: liquid hydrogen, polyethylene, water, and aluminum.
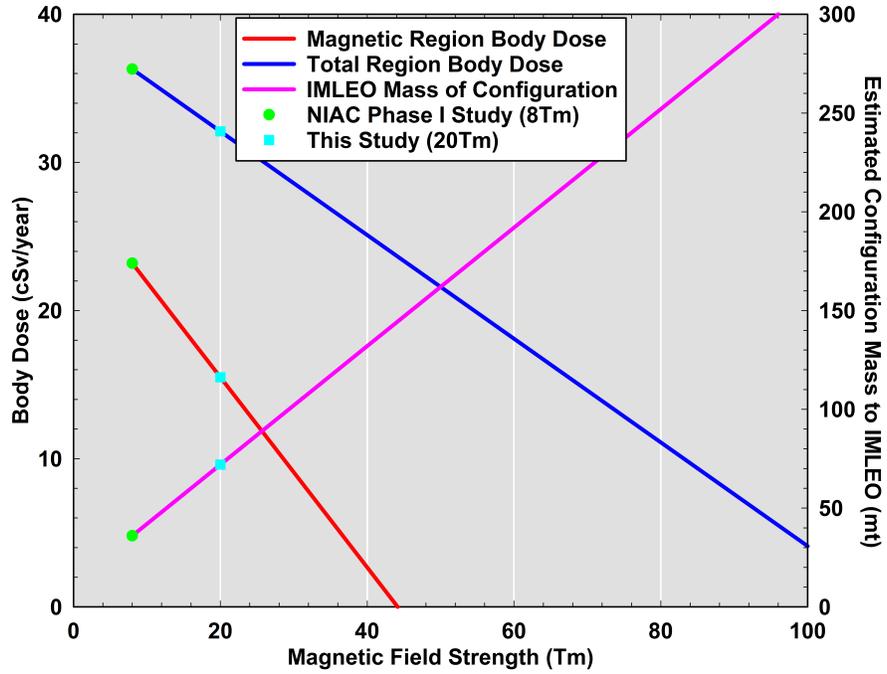
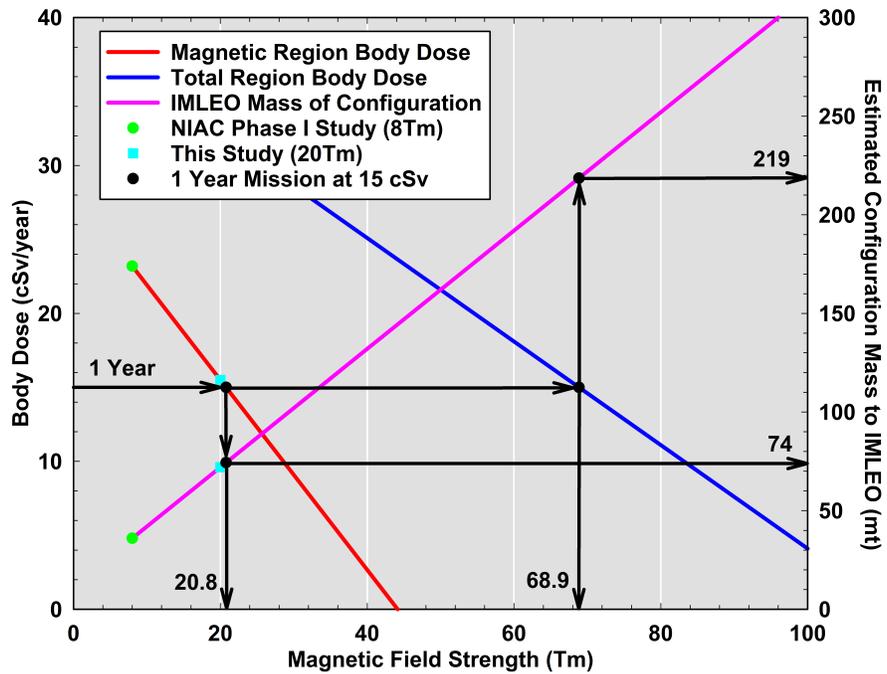Figure 9: Extrapolation curves for magnet configurations and mass.

Figure 10: Extrapolation curves for magnet configurations and mass with the 1 year mission exposure of 15 cSv.
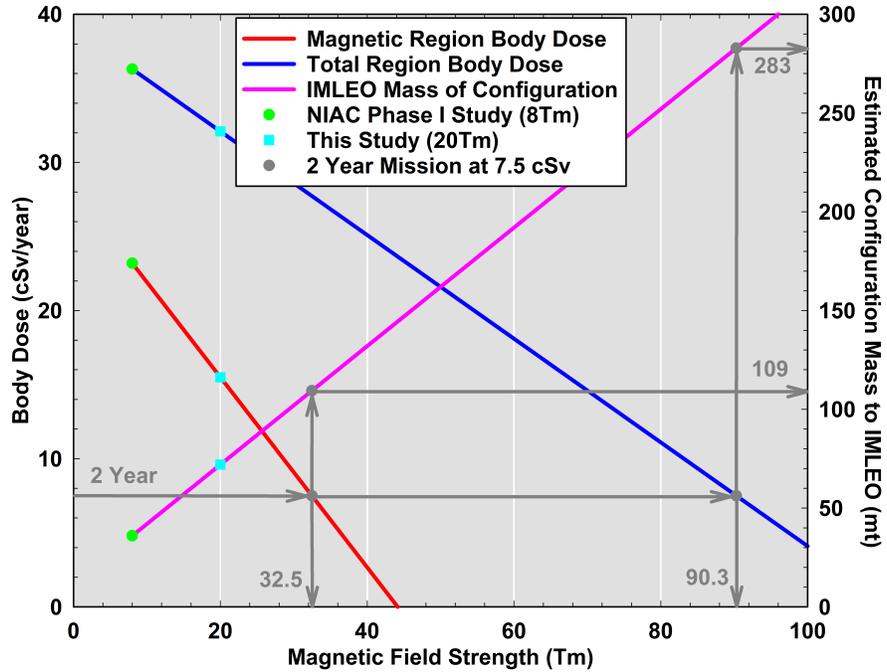
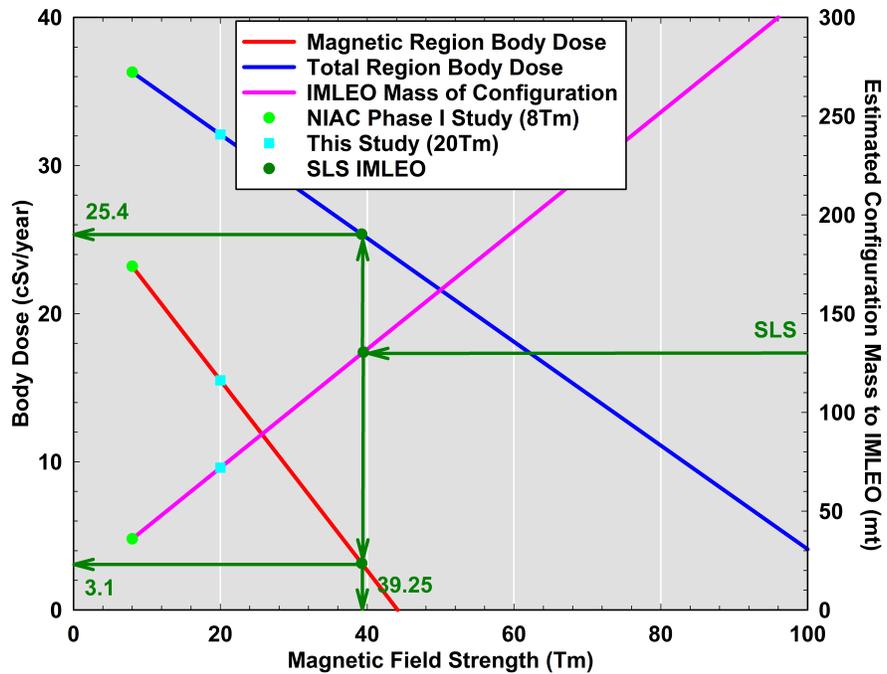Figure 11: Extrapolation curves for magnet configurations and mass with the 2 year mission exposure of 7.5 cSv.

Figure 12: Extrapolation curves for magnet configurations and mass with the SLS IMLEO launch mass of 286,000 lbm (129.73 mt).

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14. ABSTRACT

A trade study for an active shielding concept based on magnetic fields in a solenoid configuration versus mass based shielding was developed. Monte Carlo simulations were used to estimate the radiation exposure for two values of the magnetic field strength and the mass of the magnetic shield configuration. For each field strength, results were reported for the magnetic region shielding (end caps ignored) and total region shielding (end caps included but no magnetic field protection) configurations. A value of 15 cSv was chosen to be the maximum exposure for an astronaut. The radiation dose estimate over the total shield region configuration cannot be used at this time without a better understanding of the material and mass present in the end cap regions through a detailed vehicle design. The magnetic shield region configuration, assuming the end cap regions contribute zero exposure, can be launched on a single Space Launch System rocket and up to a two year mission can be supported. The magnetic shield region configuration results in two versus nine launches for a comparable mass based shielding configuration. The active shielding approach is clearly more mass efficient because of the reduced number of launches than the mass based shielding for long duration missions.

15. SUBJECT TERMS

Active Radiation Protection; Dosage; Magnetic field configurations; Radiation doseage; Shielding

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