Advanced Multifunctional MMOD Shield: Radiation Shielding Assessment

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As NASA is looking to explore further into deep space, multifunctional materials are a necessity for decreasing complexity and mass. One area where multifunctional materials could be extremely beneficial is in the micrometeoroid orbital debris (MMOD) shield. A typical MMOD shield on the International Space Station (ISS) is a stuffed whipple shield consisting of multiple layers. One of those layers is the thermal blanket, or multi-layer insulation (MLI). Increasing the MMOD effectiveness of MLI blankets, while still preserving their thermal capabilities, could allow for a less massive MMOD shield. Thus, a study was conducted to evaluate a concept MLI blanket for an MMOD shield.

In conjunction, this MLI blanket and the subsequent MMOD shield was also evaluated for its radiation shielding effectiveness towards protecting crew. The overall MMOD shielding system using the concept MLI blanket proved to only have a marginal increase in the radiation mitigating properties. Therefore, subsequent analysis was performed on various conceptual MMOD shields to determine the combination of materials that may prove superior for radiation mitigating purposes. The following paper outlines the evaluations performed and discusses the results and conclusions of this evaluation for radiation shielding effectiveness.

I. Introduction

WITH NASA's increased interest in deep space missions at various destinations, optimization of spacecraft is imperative to overcome the challenges of radiation shielding for the crew and electronics while keeping the spacecraft mass reasonable. A method proposed to accomplish this goal is through the use of multifunctional materials. One area of multifunctionality that holds promise is the micrometeoroid and orbital debris (MMOD) shields that employ radiation mitigating materials to reduce the overall radiation exposure to crew and electronics. Therefore, the focus of this study is on the MMOD shield component of the spacecraft and methods by which to increase the radiation mitigating potential of the shield while retaining the overall MMOD shielding performance.

The MMOD shield modeled for this study is a stuffed whipple shield configuration derived from the International Space Station (ISS). This configuration contains five layers (Figure 1) which were investigated for this study. The baseline configuration is the ISS configuration, where the bumper and rear wall are aluminum, the multilayer insulation (MLI) is composed of 40 layers to thermally insulate the shield, and the intermediate layers are ceramic and para-aramid materials.

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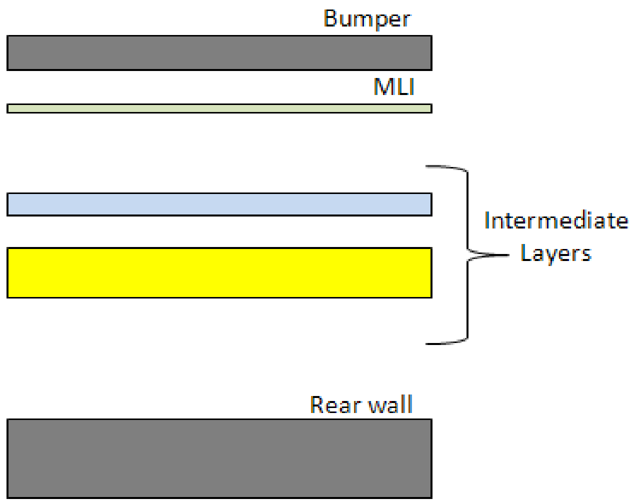

Figure 1. Stuffed whipple shield configuration.

The first part of this study focused on the MLI blanket, comparing the baseline ISS MLI blanket to a concept MLI blanket containing 43 layers of materials, including additional materials for radiation shielding such as fiberglass and polyethylene. These blankets were analyzed for radiation mitigation potential separately and as part of the overall MMOD shield. The second part of the study investigated the MMOD shielding system for radiation mitigation optimization by varying the materials in each of the different layers.

The radiation environments NASA needs to consider for deep space missions are Low Earth Orbit (LEO), the galactic cosmic ray (GCR) background radiation, and the solar particle events (SPE). The LEO environment may potentially be of less concern given that the spacecraft will most likely only be in this environment a short duration immediately after launch and again during reentry. Most of the spacecraft's time will be spent outside of the Earth's magnetic field and completely exposed to both the GCRs and SPEs. Thus, for this study, four environments were analyzed: October 1989 SPE, 1982 GCR (during solar maximum), 1987 GCR (during solar minimum), and LEO in 1970 that corresponds to an altitude of 400 km at an inclination of 51.6°.

These radiation shielding assessments were performed using the high charge and energy transport software (HZETRN), based on a one-dimensional formulation of the Boltzmann transport equation with a straight-ahead approximation[1,2]. Both the overall dose and dose equivalent were considered. The absorbed dose is typically used when discussing electronics and the dose equivalent is used when discussing biological late effects of humans. Since this study is most concerned with crew exposures during long-duration, deep space missions, the focus of the analysis will be on the dose equivalent.

II. Radiation Shielding Analysis of MLI

In the first part of the study, the MLI thermal blanket and whether additional materials to the blanket could improve the radiation mitigation properties were considered. Two configurations of the blanket were compared. The first configuration was based on the standard ISS MLI and this configuration was used as a baseline. The second configuration was the baseline MLI with additional layers added for radiation shielding protection, and was known as the "concept MLI".

Below (Table 1) are the compiled results of this comparison for the October 1989 solar particle event (SPE). The data show that the concept MLI is superior to the baseline MLI by providing a decrease in dose equivalent of 65%.

Table 1: MLI baseline comparison with concept MLI for 10-1989 SPE.

Type	Dose (cGy)	Dose Eq. (cSv)
MLI Baseline	1.43E+04	4.77E+04
Concept MLI	6.73E+03	1.66E+04
Percent increase/decrease	-52.88%	-65.14%

The following (Table 2) show results for galactic cosmic ray (GCR) exposure. In this case, the dose equivalent results show a negligible difference (less than 1%) in the comparisons.

Table 2: MLI baseline comparison with concept MLI for GCRs.

Type	GCR 1982 solar max Dose (cGy/day)	GCR 1982 solar max Dose Eq. (cSv/day)	GCR 1987 solar min Dose (cGy/day)	GCR 1987 solar min Dose Eq. (cSv/day)
MLI Baseline	1.42E-02	8.41E-02	5.90E-02	3.09E-01
Concept MLI	1.44E-02	8.40E-02	5.96E-02	3.07E-01
Percent increase/decrease	1.27%	-0.13%	0.88%	-0.55%

Finally, the MLI blankets were compared for a low earth orbit (LEO) environment (Table 3). The concept MLI showed an improvement of approximately 60% over the baseline MLI.

Table 3: MLI baseline compared with concept MLI for LEO.

Type	Dose (cGy/day)	Dose Eq. (cSv/day)
MLI Baseline	7.54E-02	2.08E-01
Concept MLI	4.74E-02	8.71E-02
Percent increase/decrease	-37.05%	-58.19%

Hence, the concept MLI outperformed the baseline MLI for both the SPE and LEO cases, but was comparable in the GCR case. In general, GCRs are very difficult to shield against because of their high energies. Thus, this result was expected for the GCR environment.

The next part of this analysis compared the overall MMOD shield using either the baseline MLI or the concept MLI. These two configurations are labeled "Baseline MMOD" and "Concept MMOD" to denote the entire MMOD shield using either the baseline MLI or the concept MLI. These two configurations were compared for the same environments as above.

The following table (Table 4) shows the results of the comparison for October 1989 SPE. For this environment, the concept MMOD shield provides only a slightly better radiation shield for crew by less than 5%.

Table 4: Comparison of baseline MMOD shield with concept MMOD shield for 10-1989 SPE.

Type	Dose (cGy)	Dose Eq. (cSv)
MMOD Baseline	3.09E+02	5.11E+02
MMOD Concept	2.95E+02	4.87E+02
Percent increase/decrease	-4.35%	-4.63%

The results for the GCR environment (Table 5) show a negligible difference (less than 1%) between the baseline MMOD shield and the concept MMOD shield.

Table 5: Comparison of baseline MMOD shield with concept MMOD shield for GCRs.

Type	GCR 1982 solarmax Dose (cGy/day)	GCR 1982 solarmax Dose Eq. (cSv/day)	GCR 1987 solarmin Dose (cGy/day)	GCR 1987 solarmin Dose Eq. (cSv/day)
MMOD Baseline	1.70E-02	8.31E-02	6.45E-02	2.71E-01
MMOD Concept	1.70E-02	8.28E-02	6.45E-02	2.69E-01
Percent increase/decrease	0.12%	-0.40%	-0.01%	-0.60%

Again the concept MMOD shield provides a negligible difference in radiation mitigation properties (approximately 1%) when compared with the baseline MMOD shield for the LEO environment, as shown in the data below (Table 6).

Table 6: Comparison of baseline MMOD shield with concept MMOD shield for LEO.

Type	Dose (cGy/day)	Dose Eq. (cSv/day)
MMOD Baseline	2.16E-02	3.22E-02
MMOD Concept	2.14E-02	3.19E-02
Percent increase/decrease	-1.06%	-1.07%

In summary, when evaluating the concept MLI against the baseline MLI, the concept MLI clearly outperformed. However, when the analysis is performed again looking at the whole MMOD system using the two MLIs, the overall performance of the two systems is comparable. Thus, the other layers in the MMOD shield have a greater effect on the overall radiation mitigating potential of the MMOD shield and their materials need to be traded as well.

III. Radiation Shielding Analysis of Various MMOD Shields

In the second part of the study, the other layers of the MMOD shield are considered and various materials and configurations are traded. For all shields considered, the MLI portion of the shield remained constant as the baseline MLI blanket. Thus, the bumper, intermediate layers, and the rear wall were the focus of the optimization. These materials were traded in various configurations to evaluate which materials and configurations would produce the ideal radiation shielding configurations. In addition, these shielding configurations were compared against the baseline ISS MMOD shield (Shield #1 in Table 7) to determine whether they fared better or worse against the current standard.

The materials and the various shield configurations are shown in Table 7. In some of the shields listed, the materials for each of the layers are the same. However, these shields considered different thicknesses of the layers. Also note that some of the materials could be in fiber/fabric form whereas others are in plate form, having potentially different densities and thus different radiation shielding outcomes.

Table 7: Shield configurations examined for radiation shielding properties.

Shield #	Bumper	Intermediate Layers	Rear Wall	Total Thickness (g/cm^2)
1	Aluminum	ceramic/para-aramid	Aluminum	2.82
2	Aluminum	ceramic/polyethylene	Aluminum	2.81
3	Aluminum	Fiberglass/ polyethylene	Aluminum	2.82
4	Aluminum	Fiberglass/ polyethylene	Aluminum	2.77
5	Aluminum/ Fiberglass	Polyethylene	Aluminum	2.75
6	Aluminum	Fiberglass/ polyethylene	Aluminum	2.82
7	Aluminum	Polyethylene	Aluminum	2.80
8	Aluminum	Polyethylene	Polyethylene	2.80
9	Aluminum	Polyethylene	Polyethylene/ Aluminum	2.80
10	Aluminum	Fiberglass/ polyethylene	Polyethylene	2.83
11	Aluminum	Polyethylene	Polyethylene	2.83
12	Aluminum	Boron Carbide	Polyethylene	2.81
13	Aluminum/ Boron Carbide	Boron Carbide	Polyethylene	2.86
14	Aluminum	Polyethylene	Polyethylene	2.73
15	Aluminum	Fiberglass/ polyethylene	Aluminum	2.78
16	Aluminum	Polyethylene	Aluminum	2.82
17	Aluminum	Silicon Carbide/ polyethylene	Aluminum	2.79
18	Aluminum/ Boron Carbide	Fiberglass/ polyethylene	Aluminum	2.83
19	Metallic Glass	Metallic Glass	Metallic Glass	2.83
20	Aluminum	Metallic Glass	Aluminum	2.76
21	Aluminum	Lithium polyethylene	Aluminum	2.77
22	Aluminum	Borated polyethylene	Aluminum	2.77
23	Aluminum	Fiberglass/ para-aramid	Aluminum	2.77

Below (Figure 2) are the compiled results for the October 1989 solar particle event (SPE). The data show that a majority of the shield configurations are comparable to the baseline shield, shield #1. There are two shields that perform worse than the baseline shield, shields 19 and 20. There are also shields that perform better than the baseline, shields 8-14. The data for each of these shields is shown in Table 8 below and their percent increase or decrease from the baseline shield is given. The shield that performed the best was shield 11, which had an approximate decrease of 40% in dose for the SPE case when compared to the baseline shield.

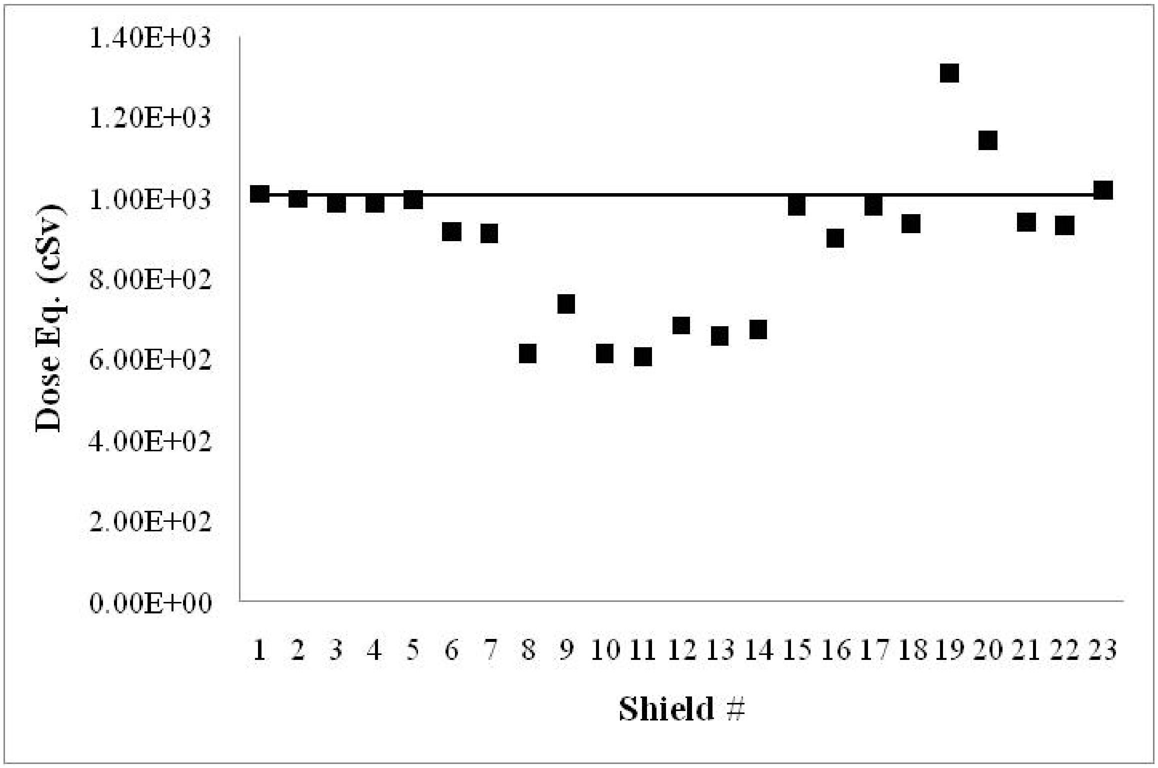

Figure 2. SPE doses for all shield configurations. The line through the data denotes the value of the baseline shield (#1) to compare with the other shield configurations.

Table 8: SPE data on shields 8-14, which performed better than the baseline shield, and shields 19-20, which performed worse than the baseline shield.

Shield #	Dose Eq. (cSv)	% increase/ decrease
1	1.01E+03	0.00%
8	6.14E+02	-39.17%
9	7.39E+02	-26.78%
10	6.15E+02	-39.05%
11	6.06E+02	-39.90%
12	6.84E+02	-32.21%
13	6.58E+02	-34.83%
14	6.75E+02	-33.14%
19	1.31E+03	29.61%
20	1.14E+03	13.02%

The GCR results are shown in the following figures (Figure 3 and Figure 4).

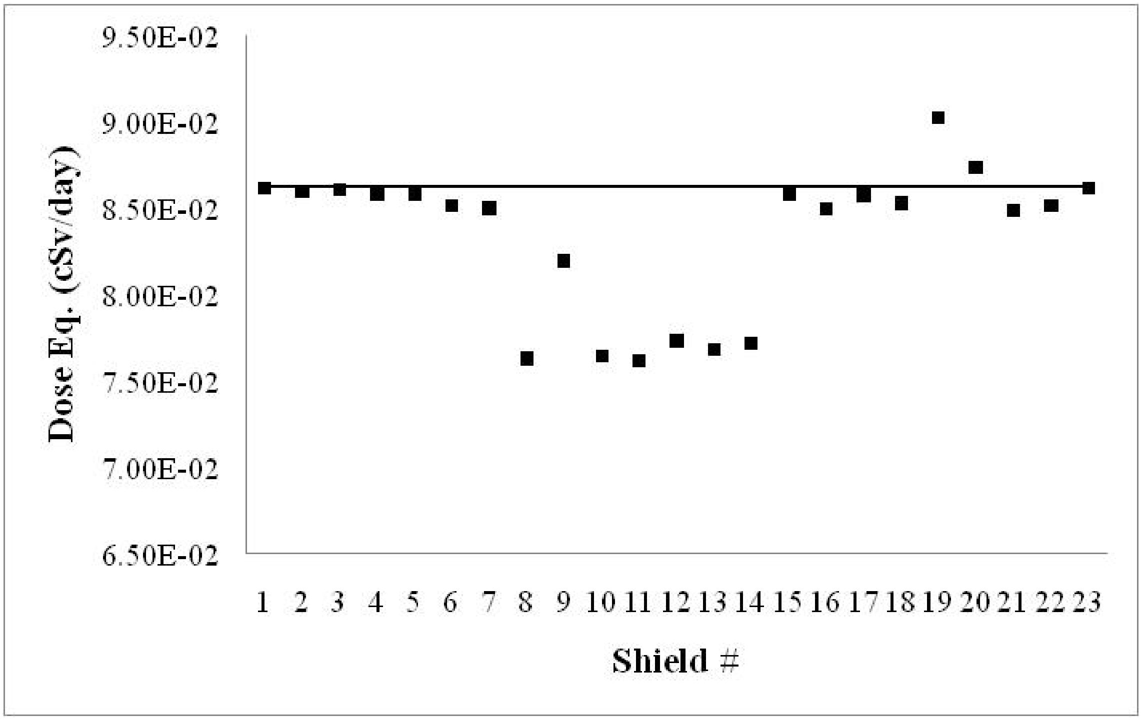

Figure 3. 1982 GCR (solar maximum) dose equivalent results for all 23 shields. The line through the data denotes the dose value of the baseline shield (#1) to compare with the other shield configurations.

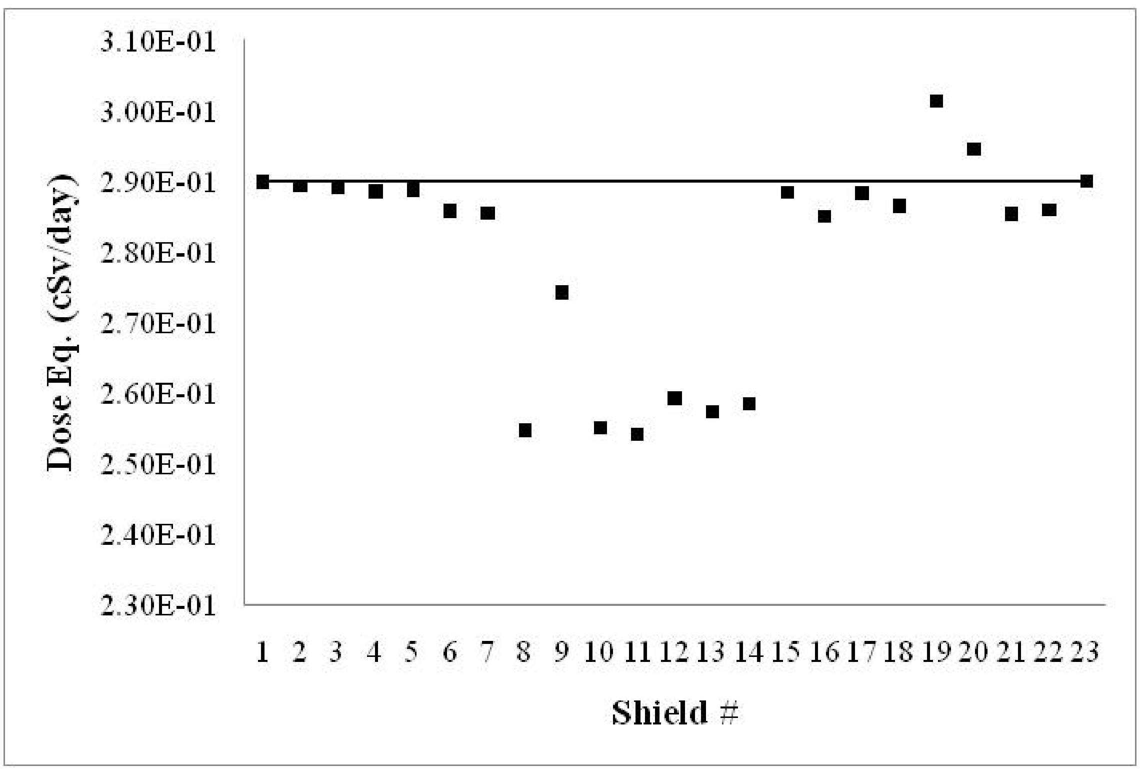

Figure 4. 1987 GCR (solar minimum) dose equivalent results for all 23 shields. The line through the data denotes the dose value of the baseline shield (#1) to compare with the other shield configurations.

Figure 3 and Figure 4 have similar results to the SPE results in that a majority of the shields are comparable to the baseline shield. Shields 19 and 20 again perform the worst with the dose equivalent for these shields with values higher than the baseline. For the GCR exposures, shields 8, and 10-14 are the best shields with respect to radiation mitigation properties. The details for these shields are shown in the table below (Table 9) and compared with the baseline shield.

Table 9: GCR data on shields 8, 10-14, which performed better than the baseline shield, and shields 23-24, which performed worse than the baseline shield.

	GCR (Solar Max)		GCR (Solar Min)	
Shield	Dose Eq. (cSv/day)	% increase/ decrease	Dose Eq. (cSv/day)	% increase/ decrease
1	8.62E-02	0.00%	2.90E-01	0.00%
8	7.63E-02	-11.48%	2.55E-01	-12.16%
10	7.65E-02	-11.34%	2.55E-01	-12.06%
11	7.62E-02	-11.62%	2.54E-01	-12.35%
12	7.74E-02	-10.28%	2.59E-01	-10.61%
13	7.69E-02	-10.88%	2.57E-01	-11.26%
14	7.72E-02	-10.45%	2.58E-01	-10.87%
19	9.03E-02	4.69%	3.01E-01	3.93%
20	8.74E-02	1.40%	2.95E-01	1.61%

The shield that performed the best was again shield 11, which had an approximate decrease of 12% in dose equivalent for both GCR cases when compared to the baseline shield. For the GCR exposures, the radiation mitigating properties of materials is far less than with the SPE exposures. This is mainly a result of the high energy GCRs, which are able to penetrate materials much more than the lower energy SPEs.

The LEO results for the shields are shown in the following graph (Figure 5).

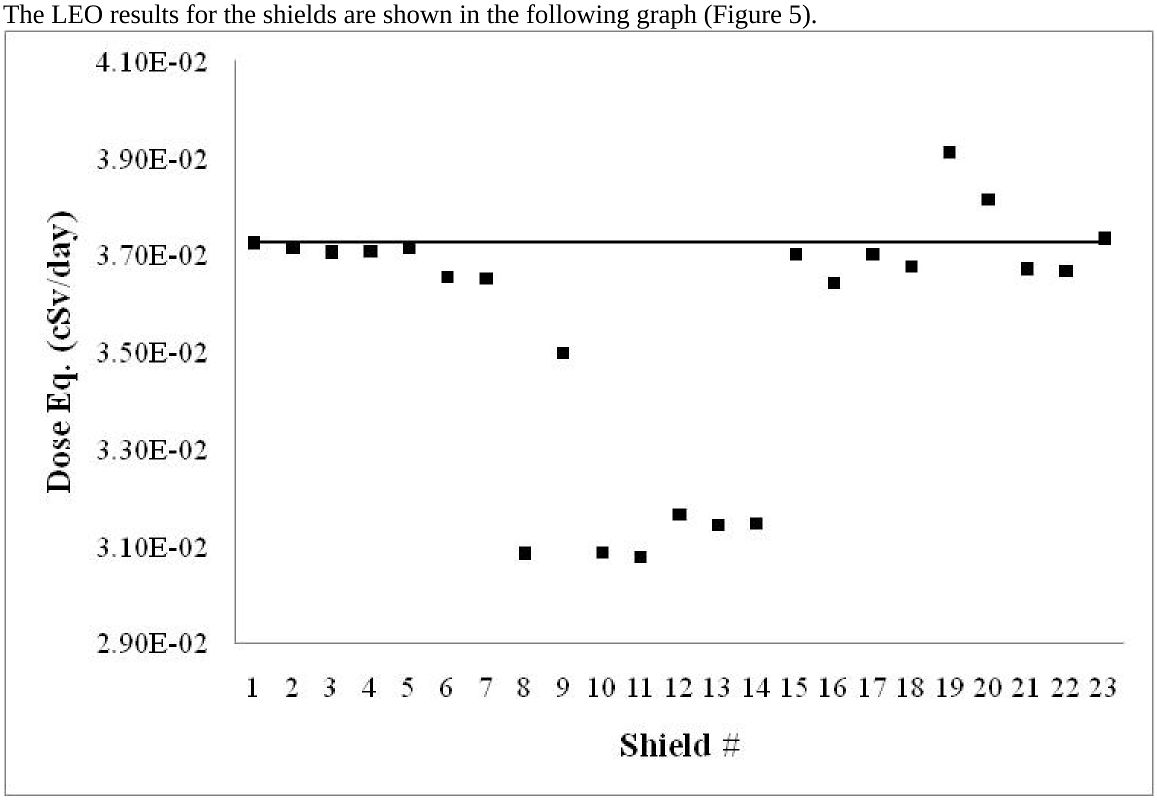

Figure 5. 1970 LEO (alt=400 km, incl = 51.6°), dose equivalent for all shields. The line through the data denotes the dose value of the baseline shield (#1) to compare with the other shield configurations.

The results for the LEO environment are very similar to the other environments in that a majority of the shields are again comparable to the baseline shield. Shields 19 and 20 again perform the worst with the dose equivalent remaining higher than the baseline. For the LEO exposures, shields 8, and 10-14 are the best shields with respect to radiation mitigation properties. The details for these shields are shown in the table below (Table 10) and are compared with the baseline shield. The shield that performed the best was again shield 11, which had an approximate decrease of 17% in dose for the LEO case when compared to the baseline shield.

Table 10: LEO data on shields 8, 10-14, which performed better than the baseline shield, and shields 19-20, which performed worse than the baseline shield.

Shield	Dose Eq. (cSv/day)	% increase/ decrease
1	3.72E-02	0.00%
8	3.09E-02	-17.16%
10	3.09E-02	-17.13%
11	3.08E-02	-17.35%
12	3.17E-02	-15.02%
13	3.14E-02	-15.59%
14	3.15E-02	-15.54%
19	3.91E-02	4.97%
20	3.81E-02	2.37%

IV. Discussion

The results showed that a majority of the MMOD shields investigated were comparable to the baseline shield. However, there were some shields that performed better than the baseline and others that performed worse than the baseline. Overall, this trend of better performers or worse performers, when compared to the baseline, was consistent regardless of environment being investigated.

The performance of the shields is a result of the respective materials used in the design. Several studies[3,4,5,6] have shown that materials containing hydrocarbons with high hydrogen content outperform other materials in radiation shielding. Furthermore, materials with high-Z elements, such as metals, could potentially increase the radiation exposure through secondary radiation production[5]. Therefore, creating an MMOD shield with a majority of materials containing high hydrogen content will be superior to other MMOD shields from a radiation shielding perspective. The table below is a subset of Table 7, showing the material and shield configurations for the best and worst shield performers of this study. In analyzing these shields (Table 11), it is apparent that the best performers are such because of the high hydrogen content materials used (polyethylene) and the worst performers are such because of the high-Z materials used (metallic glass and aluminum).

Table 11: A subset of Table 7, showing the MMOD shield configurations of the best and worst shields studied.

Shield #	Bumper	Intermediate Layers	Rear Wall	Total Thickness (g/cm^2)
1	Aluminum	ceramic/para-aramid	Aluminum	2.82
8	Aluminum	Polyethylene	Polyethylene	2.8
10	Aluminum	Fiberglass/polyethylene	Polyethylene	2.83
11	Aluminum	Polyethylene	Polyethylene	2.83
12	Aluminum	Boron Carbide	Polyethylene	2.81
13	Aluminum/Boron Carbide	Boron Carbide	Polyethylene	2.86
14	Aluminum	polyethylene	Polyethylene	2.73
19	Metallic Glass	Metallic Glass	Metallic Glass	2.83
20	Aluminum	Metallic Glass	Aluminum	2.76

The overall best radiation mitigator of all the shields investigated is shield 11, which contains aluminum for the bumper material to break up the MMOD fragments and is then backfilled with polyethylene for both the intermediate layers and rear wall. Shield 11 had a 40% decrease in SPE dose, a 17% decrease in LEO dose, and a 12% decrease in GCR dose. Thus, the shield is most effective against SPEs, which tend to be the easiest particles to mitigate because of their lower energies when compared to environments such as GCRs with much higher energies. However, there is still a slight decrease in dose with these higher energy environments as well, furthering the "As Low As Reasonably Achievable" (ALARA) principle used at NASA.

Shields 8 and 14 are also made of the same materials as shield 11 and are roughly in the same configuration. These shields performed better than the baseline and very similarly to shield 11. However, they did not mitigate as much dose as shield 11 because their overall thickness was less than shield 11. Increasing the overall thickness of the radiation mitigating materials will further decrease the overall dose to some degree, but this needs to be traded with the mass constraints of the spacecraft to determine the optimal thickness of the MMOD shield materials.

V. Conclusions and Recommendations

This study examined the various components of a stuffed whipple MMOD shield for multifunctionality as a combined MMOD and radiation shield. The first part of the study investigated the MLI blanket portion of the MMOD shield for various space environments. It was shown that a concept MLI design provided significant improvement over the baseline MLI currently in use today, when considering a SPE or LEO environment. However, when considering the overall MMOD shield configuration, the baseline MMOD shield and concept MMOD shield provided only comparable radiation shielding, with the concept MMOD shield presenting an improvement of only 5%.

The second part of this study evaluated the various other components of the overall MMOD shield, trading materials and configurations to evaluate the radiation shielding effectiveness in various space environments. These MMOD shields were compared against a baseline shield that is typical of what is currently aboard the ISS. It was shown that shields 8, and 10-14 outperformed the baseline shield consistently. Furthermore, shield 11 proved to be the best radiation mitigator of all those studied with the greatest improvement around 40%. These shields were superior to the baseline shield because of their use of materials containing high hydrogen content for the intermediate layers and rear wall. Conversely, shields 19 and 20 consistently underperformed when compared with the baseline. The increase in dose from these shields is a result of using high-z, metallic materials throughout the shield.

For future shield configurations, it is recommended to focus on low-z materials (high hydrogen content) for the intermediate layers and rear walls and to also consider graded-z configurations which may hold promise. Furthermore, if the MMOD performance of the bumper can be increased using novel materials such that less material is needed in the bumper, additional low-z material can be added to the intermediate layers or rear wall keeping the mass of the shield consistent but further increasing the radiation shielding performance. Additionally, if a novel material with low-z properties can be used for the bumper without affecting the MMOD performance, then the radiation shielding effectiveness of the overall shield might be increased further.

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