Relative threats of space debris to different parts of the space shuttle for a mission


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ABSTRACT

It is necessary to understand the conditions of the Earth’s orbital space, have design guidelines that protect spacecraft from orbital debris particle impacts, and take measures to guard against orbital debris proliferation. This paper is an attempt to study the design of spacecraft and their vulnerability to space debris, focusing on the question: what materials in spacecraft shield design can effectively prevent damage caused by collision with orbital debris and thereby improve the protection of the spacecraft? This topic examines the use of different materials in the design of spacecraft exterior to mitigate damage by collision with orbital debris.

The scope of this investigation includes the most successful technologies used to shield the International Space Station (ISS) against space debris and meteoroids. They are the Whipple Shield and the Stuffed Whipple Shield. The many factors affecting their design and effectiveness are analyzed and future improvements are discussed.

In conclusion, this research shows that there is not a unique optimal solution for the shield design of all spacecraft. There are many factors affecting the design and further research still needs to be done to find optimal combinations depending on the probable and expected space debris and meteoroids affecting planned spacecraft orbit and trajectory. In my opinion, the best solution to protect spacecraft from space debris is the Stuffed Whipple Shield using either the current materials with more innovative designs or using new materials exclusively designed and developed for the stuffing purpose.

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DEFINITIONS

**Breakup**  An explosion or disassembly of the spacecraft or launch vehicle which generates orbital debris

**Spacecraft**  A vehicle or device designed for travel or use in space

**Orbital Debris**  Any man-made object in orbit about the Earth which no longer serves a useful purpose. Objects range from spacecraft to spent launch vehicles stages to components such as trash, fragments, or other objects which are cast off or generated

**Ejecta**  Ejected particles generated from the impact of small objects on surfaces

**Spalling**  The result of reflected shock waves inside the wall thickness causing internal cracking

ABBREVIATIONS

**BLE**  Ballistic Limit Equation

**cm**  Centimeter

**ESA**  European Space Agency

**FOM**  Figure of Merit

**GEO**  Geosynchronous Orbit

**HST**  Hubble Space Telescope

**HVI**  Hypervelocity Impacts

**JSC**  Johnson Space Center

**LDEF**  Long Duration Exposure Facility

**LGG**  Light-Gas Gun

**m**  Meter

**mm**  Millimeter

**NaK**  Sodium potassium
1. INTRODUCTION

In the natural space environment meteoroids, small bits of cometary ice or rock, travel through Earth’s orbital space at an average speed of 20 km/s (44 000 mph). An average 40 000 metric tons of micrometeoroids and small dust particles enter the Earth’s atmosphere each year.¹ In geosynchronous orbits (GEO), altitudes around 35 000 km, orbital debris are a penetration hazard in interplanetary space, where they can reach velocities of approximately 70 km/s. Orbital debris is, by no means, a natural phenomenon in the space environment. It is man-made space litter resulting from 51 years of space exploration, and now the waste has increased to the point where engineers need to confront its negative resonance on space travel. Released parts of spacecraft, unintentional explosions, and defunct satellites have created a growing threat to space operations and space stations. Because space exploration is vital to civil, commercial, and national interests, it is necessary to understand the current orbital debris issue, have design guidelines that protect spacecraft² from orbital debris particle impact, and take measures to guard against orbital debris proliferation. Consequently, the topic of interest in this paper is the design of spacecraft and their vulnerability to space debris, focusing on the question: what materials in spacecraft shield design can effectively prevent damage caused by collision with orbital debris and thereby improve the protection of the spacecraft? This topic is approached by examining the use of different materials in the design of spacecraft exterior to mitigate damage by collision with orbital debris.

² Such as spaceships, satellites, space probes, robotic spacecraft, etc.
Figure 1. Shuttle STS-007 window damaged by a paint chip


2. ORBITAL DEBRIS

Since the advent of space exploration, a growing population of orbital debris has accumulated in orbits around the Earth. To minimize the potential hazard of these objects, it is necessary to understand the current orbital debris environment:

**Orbital Debris Distribution**

- Nonfunctional Spacecraft, 25.3%
- Rocket Bodies, 19.4%
- Mission-Related Items, 13.3%
- Debris from Unknown Sources, 2.0%
- Fragmentation Material, 40.0%

*Figure 2. Orbital debris distribution according to ESA as of Sep. 2007*
Each orbital debris object is classified according to one of the five debris types illustrated in figure 2. The largest population of tracked debris falls in the category of Fragmentation Material. It consists of pieces of destroyed vehicles (antisatellite tests, upper stage explosions) and fragments dislodged from satellites (paint flakes, pieces of thermal blankets). These fragments pose the highest threat because of their highest spatial density. The second largest classification is Nonfunctional Spacecraft, which are intact structures that have completed their mission or have had shortened mission life due to a nondestructive malfunction. The third category is Rocket Bodies. The aluminum bodies are converted to aluminum oxide and at the end of the combustion process; slag particles emerge from the aluminum oxide and dust particles with a diameter of up to 50 micrometers. The fourth type of orbital debris is Mission-Related Items, including explosive bolts, vehicle shrouds, etc., released during staging and spacecraft separation. This category includes a population of small particles such as sodium potassium (NaK) droplets. The final category is dedicated to debris from unknown sources.

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<th>How observed</th>
<th>Primary instrument (United States)</th>
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<td>Payloads and rocket bodies past end-of-life</td>
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<td>SSN radars, Haystack &amp; HAX radars</td>
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<td>Sodium potassium coolant droplets</td>
<td>~ 1 mm to 5 cm</td>
<td>Observed statistically</td>
<td>Haystack &amp; HAX radars</td>
<td>~55,000</td>
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<td>Solid rocket motor char, slag, and dust</td>
<td>~ 100 μm to 5 cm</td>
<td>Observed statistically</td>
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<td>unknown</td>
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<tr>
<td>Ejecta and paint flakes (degradation products)</td>
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<td>Observed statistically</td>
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3. DESIGNING FOR THE ORBITAL DEBRIS ENVIRONMENT

Spacecraft will inevitably encounter orbital debris during their functional lifetime. There are passive and active methods during the design process to protect them from damage. Passive protection includes shielding or augmenting components to withstand impact. Active protection uses sensors and warning systems to detect an impending debris impact early enough to allow spacecraft time to change position or close shutters to protect sensitive components. Active Protection is an extremely demanding and unpopular procedure. The International Space Station (ISS) is an example of a spacecraft that currently uses passive design methods to shield against orbital debris. Because of its large size (>12,000 m² surface area) and long lifetime (15 years), the ISS will be exposed to a large number of impacts from orbital debris. A variety of shield types are used to protect ISS critical items from orbital debris. The most used shields are the Whipple Shield and Nextel/Kevlar Stuffed Whipple Shield (SECTION 3.1 and SECTION 3.2).

![Image showing relative impact threat to different parts of the ISS](http://hitf.jsc.nasa.gov/hitfpub/threat/iss1.html)

*Figure 3. The images show the relative impact threat to different parts of the ISS. Red areas are the most likely to be hit, while blue areas are the least.*

Before introducing the ballistic limit equation curves, the physical phenomena that occur during the HVI event should be understood. Finally, the desirable material and configuration characteristics should be understood so that intelligent suggestions for alternate shields can be made.

3.1 WHIPPLE SHIELD

A double plate shield was introduced in 1947 by Dr. Fred Whipple to improve the protection of the spacecraft hull. This plate would be a staged or double plate structure whose purpose was to breakup the projectile at the first stage bumper into smaller, less massive, slower projectiles that could be stopped by the rear wall of the shield (the spacecraft hull). The shield was called the Whipple Shield.

Figure 4. Orbital debris impact on Whipple shield

(Christiansen, Eric L. Meteoroid/Debris Shielding. NASA-TP-2003-210788. Johnson Space Center, Houston, TX, August 2003.)

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The phase of the debris cloud materials can play a significant role in whether the rear wall can stop them or not. Generally, solids in the debris cloud are more penetrating in the rear wall than the liquid or gaseous phase metal alloys. This observation demonstrates that the bumper plate should be made of a material that will undergo a phase shift to liquid or gaseous form upon impact so that it will be less likely to penetrate the rear wall.\(^4\) Other desirable characteristics of the bumper plate are low weight; good projectile breakup qualities; large dispersion angles of the debris cloud; low expansion speed of the debris cloud; and minimal secondary ejecta.\(^5\) The bumper should be adequately thick for the majority of the projectile to be shocked (melted) to a level initially experienced upon impact, however, the bumper should also be optimally thin so that a less dense debris cloud is created. The thinner bumper yields smaller, less energetic particles that strike the rear wall over a larger area. The ideal bumper material should be flexible and lightweight to reduce launch costs. Ground testing has shown that the shockwave produced is greatest when the density of the bumper plate and the impacting projectile (orbital debris) are

\(^4\) Christiansen, Meteoroid/Debris Shielding. NASA-TP-2003-210788 (Houston, TX: Johnson Space Center, Aug. 2003) 43.
\(^5\) Christiansen 27.
the same. These two criteria are reasons why Aluminum alloy shields have been used for the bumper plate.

![Image of debris cloud](https://hitf.jsc.nasa.gov/hitfpub/testing/sampleimages.html)

*Figure 6. Flash radiography images of the debris cloud and ejecta after striking the shield*


As the debris cloud exits through the rear face of the bumper plate, the debris cloud spreads the broken wall material and fractured projectile outward radially in an expanding conical shape. It is accompanied by a pressure pulse (shock wave) and light emission. As the debris cloud expands radially, it loses kinetic energy. The particles are reduced in mass, as well as in velocity, by the bumper plate. The conical expansion of the debris cloud forces the smaller, less energetic particles to impact the rear wall over a much larger area than would have been impacted if not for the bumper plate. This spreads the damage over a larger area, but with less effect than if all the particles struck in a small area, causing cascading damage.

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The standoff distance is the area between the bumper and the rear wall. The larger the standoff distance, the more the debris cloud can expand radially. This further reduces projectile velocity while increasing the impact area. Increased standoff distances may also cause launch volumes to increase, which may restrict selection of launch vehicles or payload containers. Mass and volume constraints necessitate shield optimization which trades standoff distances, mass (thickness of plates), and predicted shield strength (stopping power). As a matter of practical design though, standoff distance between multi-plated shields is increased on the end cone portions of the ISS’ modules due to the higher probability of impact at these locations.\(^7\)

For a shield to perform effectively on orbit or to pass a ground test, there must be no holes nor light leaks. After the impact, the rear wall should continue to completely separate the space and interior spacecraft atmospheres from one another. Additionally, there should be no detached spall on the back face.

\(^7\) Christiansen 58.
of the rear wall. Spalling\(^8\) or spallation is the result of reflected shock waves inside the wall thickness causing internal cracking.\(^9\)

![Figure 8](image)

**Figure 8.** Results of a collision of a 3/8” aluminum sphere with an aluminum monolithic shield. (a) Detached spall resulting from the impact; (b) the back face of a different shield showing attached spall; (c) the cross-sectional view of the shield in (a) showing the internal material yielding detached spall; and (d) the cross-sectional view of the shield in (b) showing the internal material yielding attached spall. (Christiansen, Eric L. *Meteoroid/Debris Shielding.* NASA-TP-2003-210788. Johnson Space Center, Houston, TX, August 2003.)

On the one hand, a spall can either be attached or detached. In the case of attached spall, there are no light penetrations or perforations on the back face of the shield. A shield is considered to pass if only attached spall is present. Detached spall, on the other hand, is indicated by shield material being expelled off the back face of the shield. Although detached spalling can occur without perforation and light leaks present, it is still considered a failing indicator of a shield. Debris can be forced into the interior of the

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\(^8\) Spalling is usually produced when cratering penetrates approximately seventy percent of the rear wall thickness being struck.  
spacecraft, causing damage to equipment or injury to personnel. Shield testing and design is based on preventing both perforations of the rear wall and detached spalling from occurring.

![Detached spall](image1) ![Perforation](image2)

**Figure 9. Typical rear wall failure possibilities**

(Christiansen, Eric L. *Meteoroid/Debris Shielding*. NASA-TP-2003-210788. Johnson Space Center, Houston, TX, August 2003.)

### 3.2 STUFFED WHIPPLE SHIELD

With the invention of high-strength, lightweight materials many years after the introduction of the Whipple Shield, the basic Whipple Shield was modified so that 3M Nextel ceramic fiber and DuPont Kevlar sheets were placed between the bumper plate and rear wall to provide further protection. This shield configuration was named the Stuffed Whipple Shield. One major advantage of the Stuffed Whipple Shield over the conventional Whipple Shield is that, as a result of the impulsive loading at the rear wall, the Stuffed Whipple Shield is more likely to yield a bulge shape after impact, versus cratering or cracking, as is more commonly observed in conventional Whipple Shields. Detached spalling is less likely to occur in a Stuffed Whipple Shield than in a standard Whipple Shield. The Whipple Shield is more likely to experience perforation instead of or in conjunction with detached spalling. The presence of the Nextel and Kevlar between the two stages of the Whipple Shield helps shock and pulverize the debris cloud even further prior to the cloud striking the rear wall, reducing the projectile mass and velocity even more than already done by the bumper plate. The Kevlar also serves the role of catching many of the smallest debris cloud particles, stopping them from striking the rear wall altogether.

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11 Christiansen 43.
The selection of Nextel and Kevlar for the intermediate stage of the Stuffed Whipple Shield was based on the material characteristics and performance of each of these materials. Nextel is a woven ceramic fabric produced by 3M Corporation. It consists of Alumina-Boria–Silica fibers that induce shockwaves into any particles impacting upon it. Nextel is a series of continuous polycrystalline metal oxide fibers. In fact, the Nextel fabric is actually better at shocking the projectile fragments than Aluminum. In the Stuffed Whipple Shield, the Nextel ceramic cloth generates greater shock pressures and greater disruption of the impactor than an Aluminum bumper of equal mass, stopping fifty percent to three-hundred percent more massive projectiles than an equal mass Aluminum plate.

Kevlar is a high-strength, lightweight material produced by Dupont. Kevlar is used in many high-stress applications because of its superior resistance to heat and wear. It has a higher tensile strength than any other reinforcing material currently in the market. Kevlar consists of long molecular chains produced from poly paraphenylene teraphthalamide. The molecular chains are highly oriented with

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13 Christiansen 39.
15 People are most familiar with Kevlar being used in ballistic or bulletproof vests.
strong inter-chain bonding. That provides Kevlar’s high tensile strength versus its low mass. Kevlar has a greater strength-to-weight ratio than Aluminum. It possesses a superior ability to slow the particles in the debris cloud. Additionally, when Kevlar is impacted and penetrated, it produces less damaging particles than those metal fragments that are added to the debris cloud when an Aluminum sheet is impacted.

4. BALLISTIC LIMIT EQUATIONS

To determine the efficacy of these shields, Ballistic Limit Equations (BLE) have been developed from HVI tests and analysis to compare them. In addition, the equations are useful as a benchmark to measure the protection performance versus mass and standoff of future shield developments. The BLEs describe the particle diameter causing failure of the shield as a function of projectile impact conditions (i.e., impact speed or velocity, impact angle, and impactor density).

Hundreds of ground-based impact tests were conducted by aerospace agencies to understand the physical phenomena associated with hypervelocity impacts, and some common performance characteristics emerged. Most notably, there are three distinct impact velocity regimes: the ballistic range, the shatter range, and the melting/vaporization range.

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17 LGG at the NASA Ames Research Center (ARC) and NASA Johnson Space Center (JSC) were used to perform the hypervelocity impact (HVI) tests on ISS shields.
18 The BLEs and HVI data and analysis presented in this paper were used by NASA Johnson Space Center to fabricate shields for ISS.
19 For the BLEs presented in this paper, the particles are spherical and homogenous.
The ballistic range, sometimes called the deforming projectile regime, occurs at low impact speeds, usually less than three kilometers per second. Generally low shock pressures characterize this regime. The projectile travels too slowly to create the shock wave necessary to fragment it.\textsuperscript{20} This deformed, but intact projectile then propagates along into the rear wall or through the Nextel/ Kevlar and then to the rear wall in the case of the Stuffed Whipple Shield. Because the projectile particle remains large and intact, it maintains most of its momentum and is highly energetic; the slow impact causes more damage than if the impact velocity was greater and the projectile broke up.

The shatter or fragmentation range occurs at intermediate impact speeds, usually between three and seven kilometers per second.\textsuperscript{21} In this regime, the projectile fragments upon striking the bumper plate.

\textsuperscript{20} Phillips 3-4.
\textsuperscript{21} Christiansen 57.
and breaks up. The liquid phase of the projectile and shield material in the debris cloud is less penetrating of the rear wall than the remaining solid phase material. Thus, the shield may actually perform better when it is struck by a fixed size particle at a faster speed.

The melt/vaporization range occurs at high speeds, typically greater than seven kilometers per second. The high speed of the impact causes large shock pressures, which, in turn, leads to the formation of a mixed phase debris cloud impacting the rear wall of the shield. At some lower speeds in this regime, this multi-phasing of impact material may help the rear wall withstand the impact. The speed is often enough to perforate the rear wall regardless of the phase of the debris cloud.\textsuperscript{22}

\textbf{Figure 12. The regimes explored on a ballistic limit equation}


\textsuperscript{22} Christiansen 57-63.
These three regimes and the characteristic shape of double-plate BLEs are shown in figure 12. Any data points corresponding to a particle of the given diameter at the specified impact velocity that fall above the curve predict shield failure, while data points falling below the curve predict that the shield will not experience failure despite the hypervelocity impact by a particle of the specified size and velocity.

With the introduction of double plate shields to space applications, numerous BLEs were developed to describe or predict shield performance. There are seven commonly used predictor equations. These are the Nysmith, Wilkinson, Original Cour-Palais, Modified Cour-Palais, New Cour-Palais (or Christiansen), Burch, and Lundeberg-Stern-Bristow Equations. They only apply to the specific shield materials and configurations tested. There are two basic types of BLEs – the design equation and the performance equation. The design equation yields the minimum plate thickness for the bumper and the rear wall based upon material selection and impact characterization. These equations allow engineers to design shields so that they will withstand an impact. The performance equations predict the shield’s ability to withstand a HVI based upon the impacting projectile’s diameter and the impact velocity. Even though these BLEs are outside of the scope of this paper, the necessary conclusions and results will be stated with regard to the best equation to use when predicting Whipple and Stuffed Whipple Shield performance.

5. CURRENT SHIELD DESIGN

The Whipple and Stuffed Whipple Shields presently flown on the ISS onboard the U.S. Laboratory Module are shown in figure 13. These represent the finite element models of the module.

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23 Christiansen 32.
Figure 13. U.S. laboratory module shielding configuration

(Christiansen, Eric L. Meteoroid/Debris Shielding. NASA-TP-2003-210788. Johnson Space Center, Houston, TX, August 2003.)

For the Whipple Shields used, the bumper is made of 6061-T6 Aluminum alloy and with a thickness of 0.08 inches (2.03 mm). The spacecraft hull (rear wall) is made of 2219-T87 Aluminum alloy and is 0.19 inches (4.83 mm) thick. Similarly, for the Stuffed Whipple Shield, the bumper is made of 6061-T6 Aluminum alloy, with a thickness of 0.08 inches (2.03 mm). Layers of Nextel AF-62 ceramic fabric and Kevlar-120 high-strength weave are placed between the bumper and rear wall. Usually there are six layers of the Nextel and 6 layers of the Kevlar. The spacecraft hull, rear wall, is made of 2219-T87 Aluminum alloy and is 0.19 inches thick.

Figure 14. U.S. shielding configuration (Whipple Shield)

6. SHIELD DESIGN IMPROVEMENTS

The rear wall and bumper shields plus the standoff distance and shield thickness are crucial parts of spacecraft shields that when analyzed lead to recommendations of some promising alternate configurations for further analysis. Because BLEs are out of the scope of this paper, the values that directly link into the equations are examined while the other variables, such as thermal properties and melting temperature, are extraneous and unnecessary to explain with regard to design improvements of shields. There are six basic variables in the equations that can be examined – shield standoff distance, bumper density, bumper thickness, rear wall density, rear wall yield strength, and rear wall thickness.24

It is known that increased standoff distance between the stages of the shield has a positive effect on the rear wall’s ability to resist penetration and detached spalling. The rear wall can resist the damage because the ejecta and debris resulting from the projectile impact with the bumper is dispersed radially outward in an expanding cone. Given more distance for the conical section to expand, the ejecta and

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24 Each of these terms appears directly in the ballistic limit equations or is a term in an equation used to compute the value of a coefficient in the ballistic limit equation.
debris will lose momentum. The dispersion allows the Nextel, Kevlar, and rear wall to absorb the force of impact with less potent force, over more of its area. Theoretically, an infinite, or at least a very large, standoff distance is ideal. In general, a standoff of fifteen to thirty times the projectile size is optimum for real world systems.

There are imitations that preclude such a configuration from actually being implemented. If the ISS module has too large a diameter, it will not fit within the shuttle bay of the Space Shuttle, nor on conventional payload fairings for existing launch vehicles. Consequently, the limiting factor in standoff distance allowable is the diameter of the launch vehicle payload storage area. The added structural mass needed for spacers to increase standoff distance is also a consideration. Not only does the raw material, the spacer, cost money, but any added mass in the shields will affect the launch mass and hence launch costs. With launches costing approximately $10,000 - $30,000 per kilogram\(^{25}\), an increase in the standoff distance would most likely also increase launch costs.

Future modules could be modified to allow on-orbit access. Such modifications would allow the astronauts to replace shielding to repair damage caused by impacts. This on-orbit accessibility may not be an acceptable solution due to the added cost of or delays in launching newer elements of the space station.

The bumper must be sufficiently thick that it can shock the projectile sufficiently as it penetrates through the shield thickness. The ideal thickness is one that allows this hydrodynamic shock process to occur, but minimizes the amount of shield material that is added to the debris cloud as it is ejected out the back face of the bumper. However, there is the risk that the added thickness will also produce more bumper material in the debris cloud. Although there is uncertainty in choosing an “ideal” bumper thickness, one thing is certain; any increase in bumper thickness will necessitate additional mass added to the shield. Over a single test plate, the added mass may be minimal, but spread over an entire module, these mass increases can add up quickly and affect other things like launch costs and booster selection for launch vehicles other than the space shuttle.

\(^{25}\) Belk 11.
In theory, the thicker the shield, the better the stopping power and performance, however, this idea completely disregards mass restrictions and limitations. Instead, in choosing an alternate shield configuration, the performance of the shield versus the shield mass, material cost, and volume must be balanced. The same lack of capability for on-orbit replacement of flying shields exists in the case of the rear wall as well. Any attempt to replace the shield rear wall in orbit would automatically cause a breach of the pressure hull and expose the module to the risk of an unprotected impact from debris or micrometeoroids. Still, increasing the rear wall thickness is a feasible and viable option to improve shield performance if the accompanying increase in mass expense can be absorbed by the program.

Perhaps a better option than increasing the mass and thickness of the bumper is to choose an alternate, superior performing material. One should look at less dense and lighter weight materials that have better performance characteristics, and hence, include higher yield strengths. NASA found that Aluminum Oxide, followed by Silicon Carbide, followed by Aluminum 6061 T6 alloy are the best bumper materials based upon the eight materials they ranked for aluminum projectiles. However, these material choices do not account for other projectile types, of which steel and aluminum oxide are common.

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26 These results were obtained and ranked using an analytical model, based upon the highest impact pressure with bumpers of adequate thickness to shock the projectile completely.
types in orbit. They also do not consider material thickness (hence mass and volume) or cost in the ranking. NASA also evaluated bumper materials using a figure of merit (FOM). The materials with the greatest figures of merit are expected to perform better. Based upon NASA’s analysis of various materials, a Magnesium alloy, Tin, Lead, Cadmium, and Aluminum alloys are the top performing bumper materials, while Steel, Iron, Copper, Nickel, and Titanium are inferior. NASA’s results show that neither values nor coefficients in the BLEs are affected by changes in bumper material. However, there may be a mass savings by incorporating one of these other materials and that can lead to a slight savings in mass. With the small deviation in densities, even this savings may be so minor that the costs of implementing the new configuration far outweigh the benefit of making any change to the existing topology.

Unlike the alternate bumper material selection, the substitution of an alternative rear wall material can be beneficial; because two properties of the rear wall play directly into the BLEs, the yield strength and the density. Therefore, there are three options for improving the shield performance by changing the rear wall material. One can select a shield that is less dense (hence lighter weight) and has equal yield strength. Performance should remain the same, but there will be a mass savings. Conversely, one can select an equally dense shield. This will improve performance, but not lead to any mass savings. Finally, and most efficiently, one can select a less dense material with greater yield strength. This third option will save mass while simultaneously improving shield performance.

7. CONCLUSION

The safety of all astronauts ultimately starts with the ability to precisely predict the performance of their spacecraft. To accomplish this feat, aerospace agencies must test shields until their performance is adequately understood and the inherent risk of space debris to the astronauts is within acceptable

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27 Made up of a number of material properties including density, latent heat of fusion, melting temperature, the heat of vaporization, and the vaporization temperature
28 Christiansen 30-31.
tolerances. The cost of conducting hypervelocity ground tests in terms of time, money and manpower is a small price to pay when compared with the cost of human life, hardware and the invaluable scientific knowledge that would be lost with the failure or outright destruction of the ISS as a result of hypervelocity impacts by space debris or micrometeoroids that were inadequately shielded against. In conclusion there is not currently a unique optimal solution for the shield design of all spacecrafts. There are many factors affecting shield design and further research still needs to be done to find optimal combinations depending on the expected space debris population to be encountered and the specific spacecraft orbit and trajectory. Research suggests the best solution to protect spacecraft from space debris is the Stuffed Whipple Shield using either the current Nextel and Kevlar materials while using more innovative designs to leverage on their qualities or using new high performance materials exclusively designed and developed for the stuffing purpose. Based on this research I would suggest to carry out tests to evaluate two additional aspects of the stuffing materials: (1) the use of several alternate layers of Nextel and Kevlar material in such a manner that their fabric pattern are oriented to improve their yield strength and their capacity to catch debris particles; and, (2) change the location of the stuffing layers in the standoff in order to reduce the shock of the debris on the rear wall. In any case this represents a great engineering challenge that requires innovative designs, extensive experimentation in special facilities and the access to research and development of new materials obviously out of the scope of this paper. Besides, any finding will have to be combined with reinforcement on the spacecraft areas of higher probability of impact and use the best choice of less dense material with high yield strength for the bumper and rear walls. It is unrealistic to say that the findings in this study will alone make astronauts and the space station as a whole a safer place to live and work, but it is reasonable to assume that the knowledge gained can be used to inform and motivate others to make improvements tomorrow that will directly or indirectly impact the men and women who fly any future spacecraft.
8. BIBLIOGRAPHY

8.1. WORKS CITED


8.2. WORKS CONSULTED


