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# Design, Manufacturing, and Test of Armor for the Exploration Space Suit

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**Two business units within Collins Aerospace, Mission Systems (Houston, Texas) and Aerostructures (Chula Vista, California), partnered to design, manufacture, and test state-of-the-art armor concepts for the exploration space suit. The proposed armor concept would protect astronauts from surface impacts (slips, trips, and falls) during EVAs. Multiple armor design options were considered. Collins' selected armor concepts are sandwich composite configurations consisting of carbon fabric skins and either a titanium square-cell core or an additively manufactured (3D printed) thermoplastic honeycomb core in two orientations. The panels were designed to be sacrificial and easily replaced with on-station in-situ manufacturing capability. The Collins armor concepts were designed, fabricated, and tested. The successful test results indicate that the Collins design could withstand substantial impact energy and protect the hard upper torso.**

## Nomenclature

*AM* = Additive Manufacturing
*CAD* = Computer Aided Design
*Collins* = Collins Aerospace (Mission Systems) and Aerostructures
*EMU* = Extravehicular Mobility Unit (space suit)
*xEMU* = Exploration EMU (lunar space suit)
*HUT* = Hard Upper Torso
*ISS* = International Space Station
*NASA* = National Aeronautics and Space Administration
*NCV* = Nylon Composite with Vertical cell wall
*NCH* = Nylon Composite with Horizontal cell wall
*NCHP* = Nylon Composite with Horizontal Progressive cell wall
*NDT* = Non-Destructive Testing
*RED* = Rear Entry Door
*SAMPE* = Society for the Advancement of Material Processing and Engineering

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**Figure 1. The composite HUT demonstrator.** *Collins designed and manufactured this Hard Upper Torso (HUT) and Rear Entry Door (RED).*

## I. Introduction

Collins Aerospace Mission Systems and Aerostructures business units partnered to fabricate a composite Hard Upper Torso (HUT) and Rear Entry Door (RED) demonstrator for the next generation lunar exploration extravehicular mobility unit (xEMU or space suit) (Figure 1). Details of the composite HUT & RED demonstrator are documented in a paper submitted to the Society for the Advancement of Material Processing and Engineering (SAMPE) Conference 2021. While the number of plies were designed to meet static loading conditions, the weight penalty for meeting NASA's impact requirement was estimated to be substantial.

NASA's 2020 EVA System Maturation Team Gap List[2] identified Mass/Strength Optimized Composites as a technology gap, primarily due to the severe impact criteria. From Collins' perspective, two options exist: sizing one laminate material and thickness to withstand both the specified impact requirement, which is quite high, and all other structural loads (like internal pressure), or designing a detachable armor to withstand possible impact damage so that the main HUT structure is only responsible for the normal structural loads (like internal pressure). While awaiting the results of NASA's impact probability data to be published, Collins' initial calculations seem to indicate that the latter solution would be more weight-efficient, i.e. having a separate structural system to address the more significant impact loads. However, both approaches were considered for identifying future manufacturing concepts. Hybrid solutions are also possible.

If the former solution had been pursued (one structure to withsand impact and internal pressure), a material change would likely be required. The Z2 spacesuit, NASA's 2014 prototype, sandwiched carbon between S2 glass to improve impact resistance, which increased weight of the suit not needed for pressure and operating loads[3]. Collins also considered switching from a thermoset to a thermoplastic matrix for the composite HUT, which is known to perform much better than thermosets during impact. While thermoplastic composite manufacturing processes are significantly different from thermosets, Collins has made considerable advances in thermoplastic structures development over the last three years and determined some reasonable design and fabrication approaches for this solution. In the end, a thermoset material was chosen because of its more mature manufacturing processes and more thorough characterization (material properties database).

The team chose to design separate pieces of armor that could be affixed to the main structure of the HUT with Velcro and replaced as necessary. Multiple designs were chosen, manufactured, and tested. Results are presented and discussed.

# II. Background

For years, hard and soft suits were developed in parallel. The current space suit is a hybrid design with a rigid HUT and brief to which the soft components of the suit attach[4]. The EMU has worked well on the space station, which is a relatively clean and safe environment compared to the surface of a planet or moon.

"Unlike the International Space Station (ISS), where the great majority of both scientific and operational tasks are internal to the habitat, for both the Moon and Mars, the purpose of being there is to explore: extended surface traverses, detailed geological surveys, and direct human involvement in surveying and sampling as far from the landing site as technology will allow."[4] Because of that new mission, a new space suit was designed.

Actually, several iterations of suits were designed and tested. Most recently, the Z-2 Prototype Space Suit was fabricated using a laminate sandwich structure of S-glass and carbon fiber for the hard components (HUT, RED, and brief). Analysis and test determined this hybrid material improved impact performance but it was also reported that the stresses and deformations due to impact were an order of magnitude higher than the static loads[3,5,6]. For this project, Collins segregated the problem and provided a weight-optimal design for the static pressure loads and a tailorable add-on sacrificial solution specific to impact threats.

# III. State of the Art Armor

Armor designed to protect people (rather than vehicles or facilities) typically falls into two major categories: ballistics and sports. The ballistic armor for soldiers is designed to stop bullets or other supersonic projectiles and is typically made of ceramics or kevlar[7,8,9,10]. For low velocity, high mass impact sports, flexible material and padding is generally used, though hard sections may be integrated into the design[11,12,13].

Ballistic armor is typically made of heavy ceramic plates and/or Kevlar layers. Some ballistic armor incorporates honeycomb structures which can offer better specific energy absorption[8,9]. Another lesson learned from studying soldier-worn armor is to secure it with Velcro[7].

Many instances were found of sports armor secured with Velcro straps[11]. A number of them also incorporated a honeycomb design[12]. Generally, honeycomb structures are found to be more specifically energy absorbent than foam. For example, the Hexr bike helmet uses an additive-manufactured stiff polymer in a hexagonal configuration, which the manufacturer claims is "safer" than foam helmets. For Hexr, "safer" in this instance is defined as able to better withstand oblique tests by 26%[13]. Also, Hexr points out that creating the honeycomb via additive manufacturing is the only reasonable way to manufacture honeycomb core on a compound curvature. Similar to the HUT in this respect, additive manufacturing was considered during our design phase.

# IV. Design

## A. Design Parameters

To protect the space suit's HUT from a potential impact is challenging because internal pressure must be maintained during and after the impact. Additionally, the solution must not impede the astronaut's mobility or get in the way of performing required tasks.

Ultimate design optimization will not be possible without probabilistic threat assessment data, incorporating likely impact sites, frequency, energy level and incident angle. Furthermore, the fact that impacts will occur in remote regions with limited tools is an additional design-criteria that must be considered. That is, the solution must be easily repaired or replaced with minimal or no tools.

With all of this in mind, the team listed the key design criteria. The armor must:

- ✓ prevent depressurization of the spacesuit
- ✓ not obstruct the astronaut's mobility
- ✓ protect the astronaut from falls
- ✓ be lightweight
- ✓ be easy to repair or replace (preferably without tools)
- ✓ be made of a quality, non-hazardous material
- ✓ be cost-efficient in life cycle

## B. Consideration of the Load Path

No matter which armor design is chosen, the load that passes through the armor must make its way into the structure of the spacesuit. This load path from the armor to the spacesuit needs to be carefully designed such that the spacesuit is not damaged at attachment points. After an impact occurs, the spacesuit's structure still needs to maintain pressure and maintain its ability to endure the normal load cases (handling, moon's gravity, etc.).

### C. Design Options

As previously discussed, one can approach the design with the intent of a solid laminate, capable of sustaining structural and operational loads along with impact events, similar to the Z-2 suit. Or, as is proposed herein, one can split the static structural design from the portion of the suit that protects from an impact. As the Japanese Samurai learned, a damaged scale on their armor could be easily replaced. The team selected a similar architecture using discreet panels that can be easily and quickly replaced, albeit much larger than Samurai armor scales.

Collins settled on a carbon fiber and honeycomb core sandwich composite structure as the basis for the armor. The facesheets can provide puncture resistance and the internal honeycomb core can absorb tremendous blunt force energy via compression. The back face sheet will provide integrity and reinforcement to the structure when it is locally damaged and ensure the underlying spacesuit structure (pressure vessel) is undamaged by the impact. Collins uses sandwich structures in many aerospace components and has ample experience designing, optimizing, manufacturing, and repairing sandwich composite structures.

The armor panel would be sacrificial. That is, it would be replaced after absorbing an impact resulting in damage. Replacing an armor panel will be less expnsive and easier than replacing the entire HUT.

Multiple fastening solutions were investigated to meet the "easily replaceable" criteria. Some of the design solutions considered for attaching the armor to the spacesuit included:

A. Fastener-less, using guide pins or features
B. Fastened using shear pins
C. Slotted connections with tabs on the armor
D. Flexible latches, pins, snaps, or Velcro

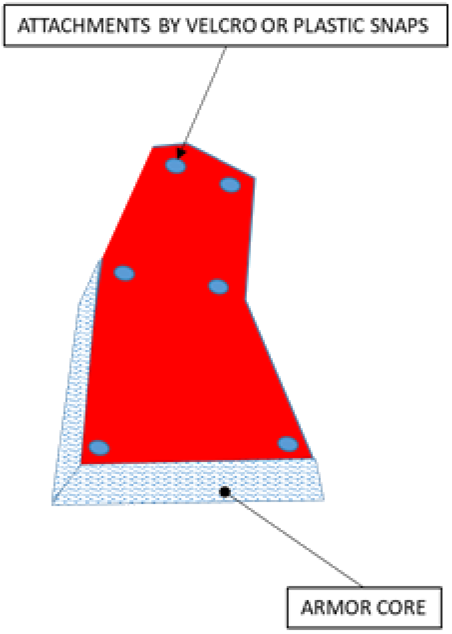

**Figure 2. Armor attachment concept.** *Four different versions of the sandwich armor were designed, built, and tested.*

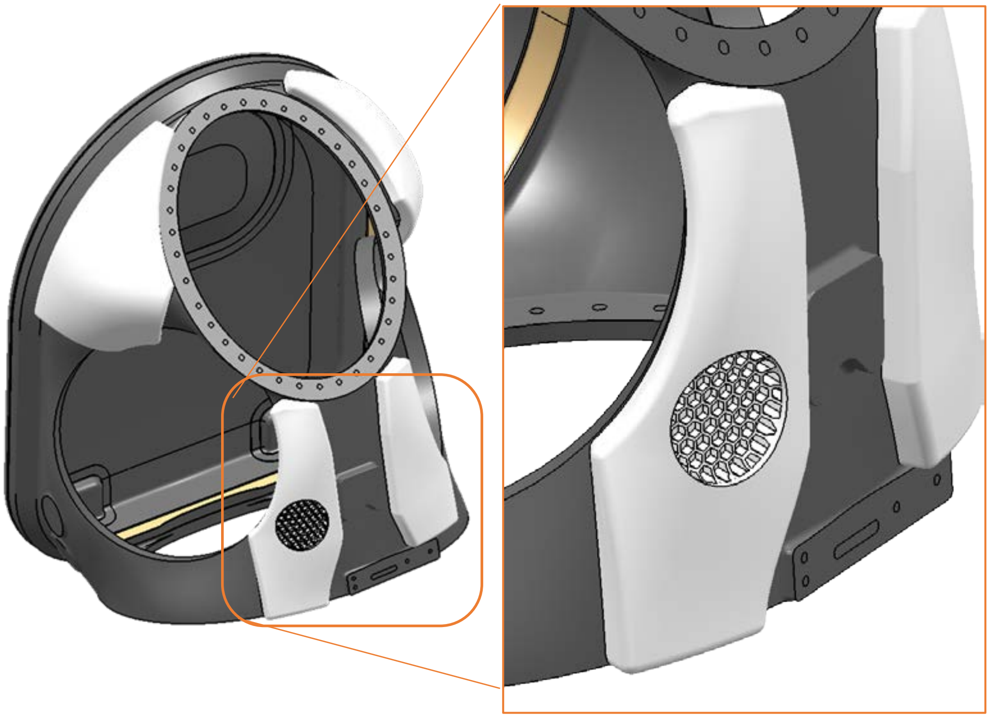

**Figure 3. Armor demonstrator.** ***This screenshot from CAD indicates the areas where armor could be placed (armor is depicted in white). The circular cutout is a cross-section to show the honeycomb structure within the armor.***

**Figure 4. Armor Prototype attached to the HUT demonstrator.** *This AM armor (outline was created to demonstrate how the armor piece would fit onto the HUT.*

## D. Materials Research

There are many possible materials that could be used for the armor. State of the art candidates included various foams, metals (including titanium), and polymeric additively manufactured (AM) materials. Collins chose to test a thermoset carbon fiber reinforced epoxy composite for the skins and a honeycomb core of various designs. Collins frequently builds components using carbon fiber reinforced epoxy composites and chose Hexcel AS4/8552 as the material for the face sheets of the armor. Given time and resources, a thermoplastic composite skin is certainly achievable, and may produce superior protection.

A proprietary titanium core with corrugated square cell was tested. This material is commonly used in civil aviation jet engine nacelles for its light weight strength and environmental resistance. Here it mates well with carbon fiber without creating a significant galvanic couple (as would aluminum).

As commented in Atkins[4], (ICES, 2015) "While the access to Earth or shorter duration missions may favor the use of a fabric-based solution [space suit], the specialized equipment and high levels of required technical skills make this design difficult to maintain and repair on extended missions. One potential mitigation for this is the use of state-of-the-art fabrication techniques, such as additive manufacturing, in conjunction with wider use of hard-suit components."

Thermoplastic materials are well-proven in additive manufacturing, while titanium is commonly used in the aircraft industry for its strength and lightweight designs. These materials were considered for use in the armor-coupon-tests. However, building the curved armor using traditional manufacturing methods would be difficult and titanium AM is uncommon in space. Many thermoplastics are currently used in AM, some mixed with milled fiber reinforcement. The ISS has a 3D printer that has proven the technology works in a microgravity environment.[14]

### E. Armor Test Specimen

The armor concept was tested using small coupons of various construction. They all had the same outer skin construction, but the choice of energy–absorbing honeycomb core varied from coupon to coupon.

A laminate coupon was placed underneath the armor-coupon to approximate the underlying structure of the spacesuit. A successful armor design could sustain significant damage to itself, but the requirement was to prevent damage to the underlying laminate coupon representing the space suit. Figure 5 shows the notional arrangement, and Figure 6 shows the detailes of the titanium honeycomb test panels.

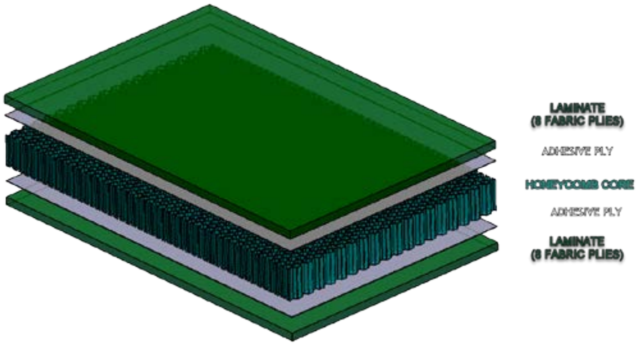

**Figure 5. Layer stack up**. *The honeycomb layer is sandwiched between solid sheets of carbon fiber composite.*

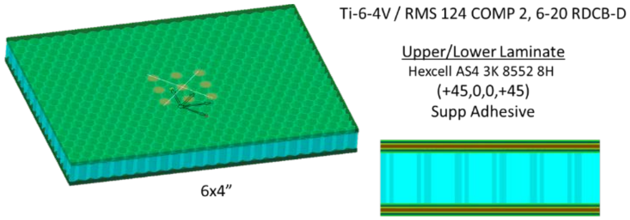

**Figure 6. Titanium Test Coupon.** *Ti sample, titanium vertical cell wall test specimen.*

The other three cores (Figures 7, 8 and 9) are built with additive manufacturing, using a carbon fiber loaded Nylon 12. The core was printed as a hexagonal pattern with L=3/8 in with a minimum thickness of 0.040 in, ensuring the walls are not too thin after being printed.

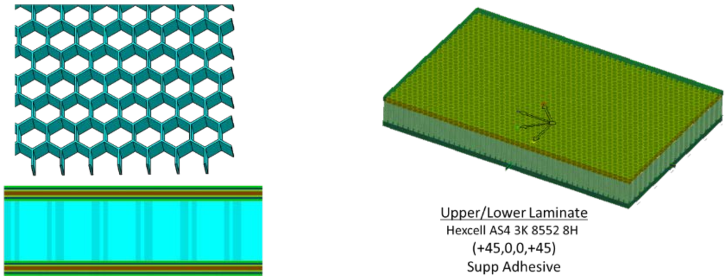

**Figure 7. Armor Test Coupon 1 and 2.** *NCV sample, nylon 12 composite with vertical cell-wall.*

Armor Test #2 has vertical walls, normal to the face sheets, and Armor Test 3 and 4 have walls and cells parallel to the face sheets but with different cell-wall thicknesses, playing with progressive and constant wall thicknesses, respectively (see Figure 8).

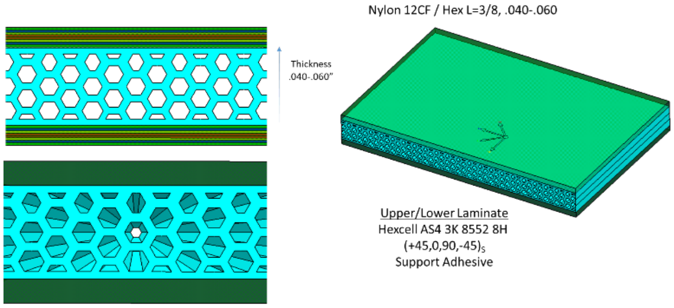

**Figure 8. Armor Test Coupon 3.** *NCH and NCHP samples, nylon 12 composite with horizontal cell wall. NCHP has progressively thicker cell walls.*

## V. Tests

### A. Test Set Up

Figure 9 shows the six-foot drop test stand. The impactor was a two-inch diameter steel semi-sphere, which was attached to a 36.1 lb weight and dropped from six inches, one foot, three feet, and four feet for a maximum of 140 ft-lbs maximum. Tests were performed on the various samples at Collins' Riverside, California facility.

**Figure 9. Drop Test Stand.** *Patrick Nolan and Roberto Ramos film the test using a high speed camera.*

## B. Samples

Figure 10 shows the honeycomb core of the test samples, which were manufactured on a 3D-printer using nylon 12 material. The titanium samples weighed less than the nylon samples due to the titanium core's smaller ribbon thickness, and the minimum manufacturable printed wall thickness of the Nylon material. Note that the density of titanium is 0.16 lbs/in$^3$, while nylon 12's density is 0.036 lbs/in$^3$.

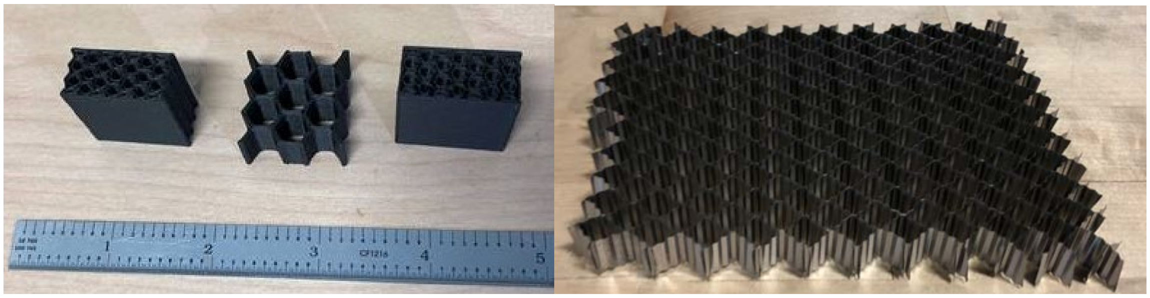

**Figure 11. Core of Samples.** *The core of the samples were a honeycombed structure. The AM nylon and titanium samples have slightly different patterns.*

Figure 12 is a photograph of some of the samples prior to testing. The dimensions of each coupon are 4in by 6in with each cores height at 0.5in. The laminates were bonded to the cores using Henkel EA9321 and left to cure at room temperature for 24 hours. Four test specimens where fabricated plus one spare for each core type. Their thickness and weight were recorded in Table 1.

**Figure 12. Samples pre-test.**

## C. Test Results

Figure 13 shows the samples post-test. As indicated in Table 1, the maximum indentation in the nylon samples as 0.1in, which was a fraction of the thickness of the samples. Future samples may be thinner to determine the optimal thickness, although that determination should be made after the exact impact specifications are provided by NASA.

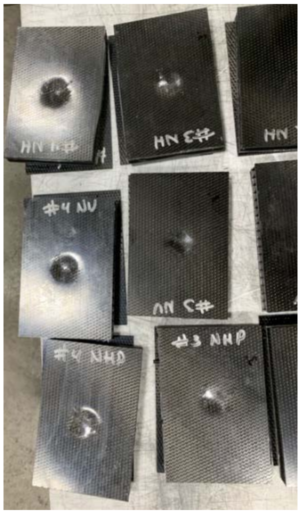

**Figure 13. Samples post-test.** *The maximum indentation on the nylon samples was 0.1in, as shown in Table 1. The back skins of the samples were not damaged, as confirmed by ultrasonic scan.*

| ID | Specimen | Height (ft) | Weight (g) | Impact Depth (in) |
|---|---|---|---|---|
| 1 | Ti | 0.5 | 178.8 | 0.013 |
| 2 | Ti | 1 | 176.8 | 0.020 |
| 3 | Ti | 3 | 177.4 | 0.242 |
| 4 | Ti | 2 | 176.4 | 0.030 |
| 1 | NCV | 0.5 | 220.9 | 0.010 |
| 2 | NCV | 1 | 219.4 | 0.015 |
| 3 | NCV | 3 | 224.2 | 0.036 |
| 4 | NCV | 4 | 216.6 | 0.105 |
| 1 | NCH | 0.5 | 270.6 | 0.100 |
| 2 | NCH | 1 | 264 | 0.014 |
| 3 | NCH | 3 | 272.6 | 0.067 |
| 4 | NCH | 4 | 367.1 | 0.111 |
| 1 | NCHP | 0.5 | 280.8 | 0.008 |
| 2 | NCHP | 1 | 269.6 | 0.014 |
| 3 | NCHP | 3 | 274 | 0.071 |
| 4 | NCHP | 4 | 271.5 | 0.161 |

**Table 1. Depth of impact.** *Ti = titanium, NCV = nylon composite vertical, NCH = nylon composite horizontal, NCHP = nylon composite horizontal progressive (thinner wall thickness).*

In all cases, the back skin visually appeared to be undamaged, which was later confirmed by non-destructive testing (NDT) using A-SCAN. The fact that the back skin was undamaged indicates that the armor fully absorbed the impact.

### D. Test Summary

The samples fully absorbed the 140 ft-lb impact with a maximum indentation of 0.1in. Therefore, the tests could be repeated with thinner samples to determine the optimal thickness. However, the exact impact force should be known and evaluated prior to adjusting the dimensions of the samples.

While the titanium weighed less and had less of an indentation, nylon is more likely to be used in the future, as discussed in the Materials Research section. Both materials survived the tests successfully and would be viable options for future development.

## VI. Future Development

Other materials can be investigated, such as thermoplastic composites, graphene additives, and fibers such as Kevlar that could improve puncture resistance. The addition of foams to the honeycomb cores could also be evaluated to improve impact energy absorption. Thanks to the freedom of 3D printing, geomtric variations should also be evaluated to determine the design with the least mass. Fluted cores are one of the most promising printable designs if the height envelope of the armor allows it (Figure 14).

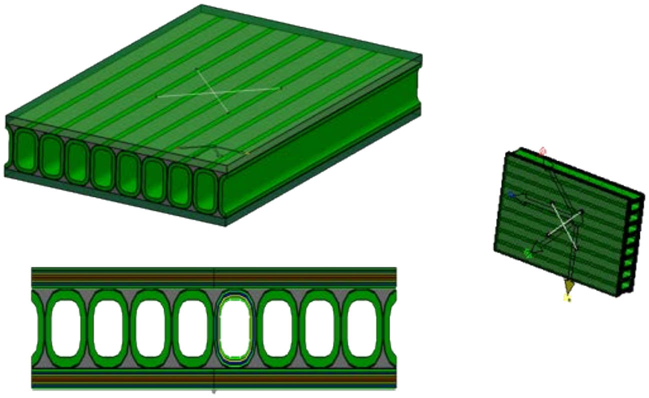

**Figure 14. Fluted Core Armor Concept.**

In general, the core could be strengthened in areas with the highest impact risk probability and energy. Conversely, the areas with the least impact risk could have thinner or less dense armor to reduce mass.

There are potential additional constraints that were not considered that might reduce material options including radioactive resistance, radio frequency permeability, and/or electrical conductivity (to prevent buildup of static charge). If meteoroid resistance were required, some other material may be added to the layer stackup.

Lastly, there are more novel core ideas to be investigated like the possible combination of multiple layers (two decks of cores separated by a septum) and cores with different shapes.

## VII. Conclusion

Based on NASA's 2020 EVA System Maturation Team Gap List[2], which identified Mass/Strength Optimized Composites as a technology gap, Collins chose to design pieces of armor that could be affixed to the HUT with Velcro and replaced as necessary. Multiple designs were chosen, manufactured, and tested. The successful test results indicate that the design could withstand impacts up to 140 ft-lbs and provide protection to the HUT.

Collins' patent-pending design includes Velcro for easy assembly and disassembly, armor that can be 3D printed in a space station, habitat, or vehicle for deep-space missions, and a low mass structure. This work paved a foundation for Collins' armor design and allows the team to develop future energy absorption systems. While future work could optimize the placement, thickness, and geometry of the armor, these initial experiments were promising.

## Acknowledgments

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