MMOD Protection through Orbital Additive Manufacturing

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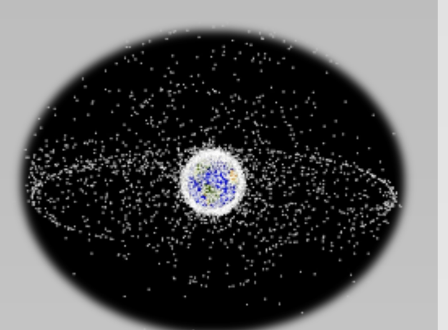
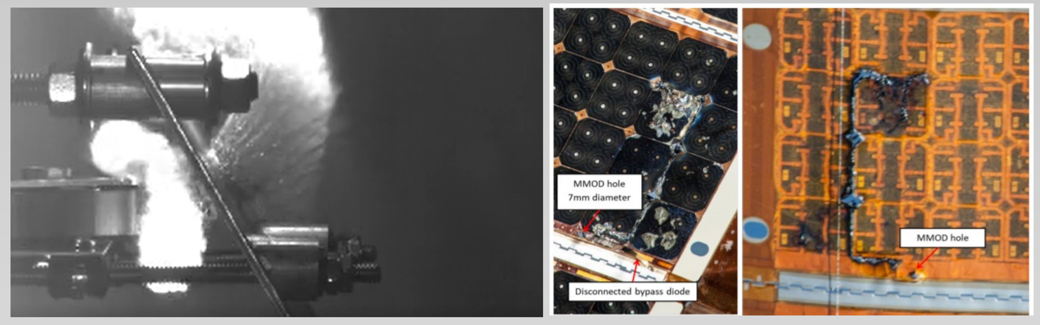
Problem

Untraceable micrometeoroids and orbital debris (MMOD) travelling at speeds of 1-20 km/s pose a serious threat to space assets. Despite their small size, the extreme velocities of these space objects creates the potential for catastrophic damage. Existing shielding methods are limited by traditional manufacturing methods and are costly to employ in the space domain due to high costs of weight and volume in transporting material to space.

- USSF/NASA currently tracks ~20,000 artificial space objects
  - Size Threshold: 5-10 cm LEO ; 0.3-1.0 m GEO
- Untraceable micrometeoroids and orbital debris – **can mitigate risk**
  - Average Velocity: up to 10 km/s
  - High Energy Impact = damage



Below images illustrate the destructive power of an MMOD strike (left) impact of a solar panel drive mechanism (right) short circuit of solar panel caused by MMOD strike



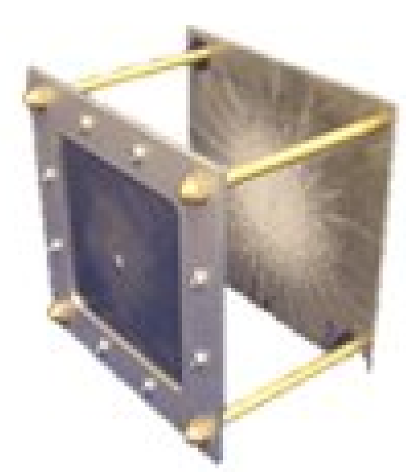
Private Sector Innovation = New Capabilities

- **"*Made In Space* (MIS) solution for in space manufacturing"**
- **Combination of Robotics and Additive Manufacturing (AM) to construct space assets in space.**
  - Repair and Reconstruction
  - Circumvents launch size constraints
  - Reduces costs and furthers exploration possibilities

Project Goal: Leverage 3D printing technology and geometry to protect on-orbit structures from MMOD

Solution

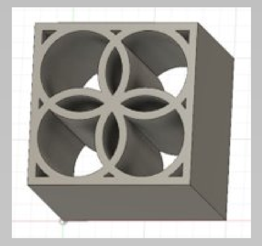
- Historical Solution: Whipple Shield.
- --Made of aluminum plates – impact plate breaks up projectile. Rear plate stops fragmentation cloud
- --Requires large launch volume
- --Requires on-earth manufacturing
- Future Solution: Use MIS innovation of 3D printing on orbit to design a new shield to effectively defend against MMOD strikes.



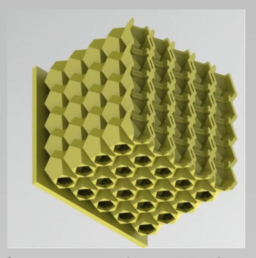
Innovation

On Orbit Additive Manufacturing:

- The ability to 3D print structures while on orbit fosters design freedom
- Complex geometries to be quickly manufactured in microgravity environment (no need for support material)
- Allows designers to neglect constraints of the hostile, launch environment.
- For this specific project, a unique, space-grade thermoplastic called **ULTEM** is the build material. ULTEM has been proven by *Made In Space, Inc* in their on-orbit 3D printers. The proposed approach of retrofitting orbiting space assets with protective shields that are built and installed on orbit is completely revolutionary! This capability makes it possible to employ completely unique designs that are more effective, but would otherwise not survive the launch in orbit



Concentric cylinder design



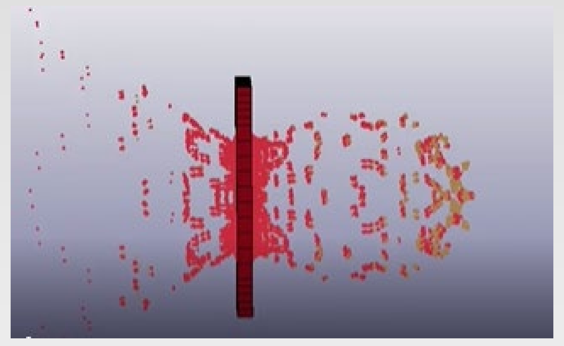
Model of a complex Kelvin structure

Innovative Ideation Process:

- Multiple ideations methods were used to generate over **90 individual designs.** These methods include:
  - 6-3-5 Ideation
  - Historical Innovators Ideation
  - TIPS Ideation
- The top ideas were selected based on compliance with customer needs and design requirements.

Innovative Design Techniques:

- Finite element analysis (FEA) and hypervelocity testing were used to ensure all design avenues were considered.
- FEA used was Ansys LS-DYNA Smoothed Particle Hydrodynamics (SPH)
- This was used to build the foundation of designs by analyzing how ULTEM reacts in a hypervelocity impact



FEA simulation of hypervelocity impact

- Proactively sought out hypervelocity testing facility and made lasting connections with Texas A&M. A two-stage light gas gun at Texas A&M's hypervelocity impact lab (pictured below) was used to test shield designs in a hypervelocity environment.
- There are a limited number of two-stage light gas guns in the nation.
- The data obtained from hypervelocity testing aided in shield design iterations.

Two-stage light gas gun at Texas A&M

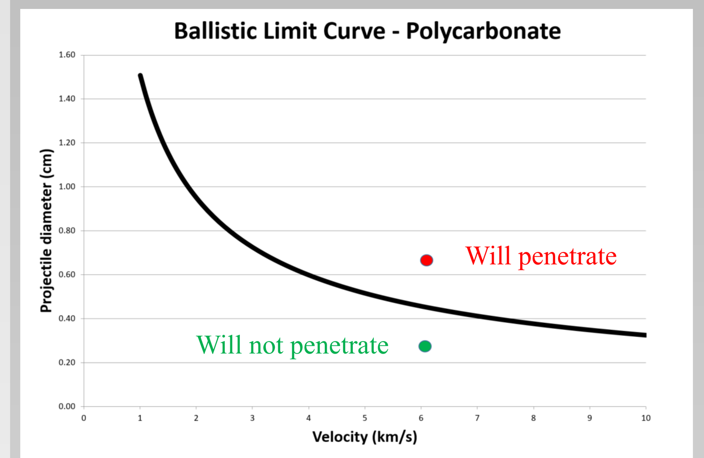
Continued Work:

- The goal of this project is to have a working technology demonstrator that will be able to fully stop MMOD within the desired range.
- Future work would include designing an attachment method to put the shield on the satellite
- Finding the best method to print the shield in a zero g environment would be another area for further development.

Technical Development

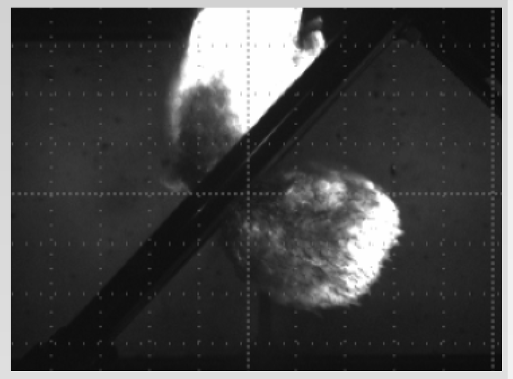
Approach: Hypervelocity impact shielding with a novel material and a non-standard manufacturing process does not have a closed form solution for analysis. Predicting impacts analytically rests on Ballistic Limit Equations (BLEs) that are developed empirically for a specific material and configuration. As such, we designed MMOD shields with the following, iterative steps.

1. Background research
2. NASA and MIS SME advising
3. Comparable-material BLE verification
4. Phase 1 - material property testing
5. Prototype with SME iteration
6. Phase 2 - shield testing
7. Design iteration with SME
8. Phase 3 – shield testing



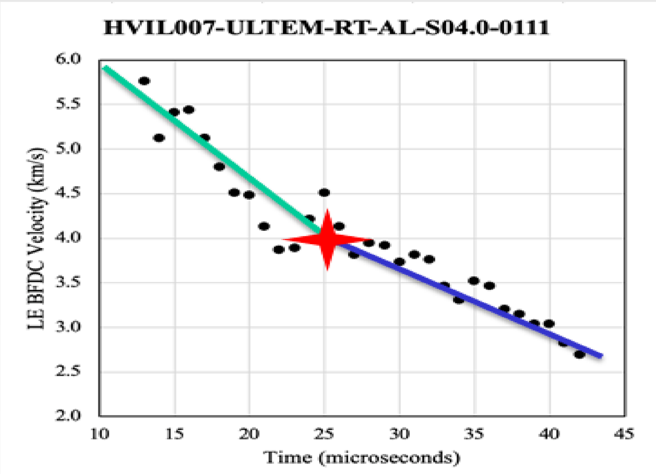
BLE Material Verification: Polycarbonate has similar material properties to ULTEM. Curve is developed with a given plate thickness. Projectile diameter-velocity combinations above the curve will penetrate the plate, and those below will not.

Phase 1 Testing



¼" Plate *Normal Impact* *vs.* *1/8" Plate Oblique Impact (45°)*

- Oblique Impacts show greater decrease in velocity – suggests greater energy dispersion
- Future Testing required to determine if this is due to redirection, or simply more material through which the projectile must penetrate.



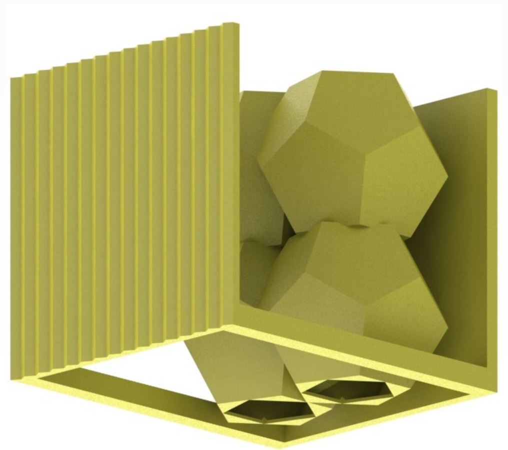
Back face debris cloud velocity of ¼" plate; normal impact at 6.192 km/s

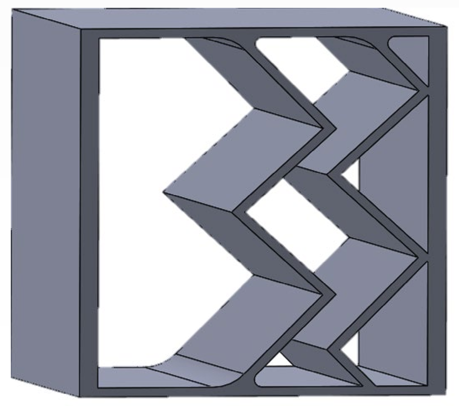
Phase 1 Testing Conclusions:

- Stand-off distance = **5.7 cm** for optimum energy dispersion/volume
- Quasi-Isotropic pattern to help prevent material decomposition

Shield Designs incorporating Phase 1 Testing Conclusions

Impact Direction





Warfighter Impact

"Space debris poses a further risk to the development of human activity in space"

- US Space Force Capstone Publication

Increased use of space domain by militarized threats and private sector = more MMOD risk and risk of mission failure. This technology will be an important defense against future hostile activity.

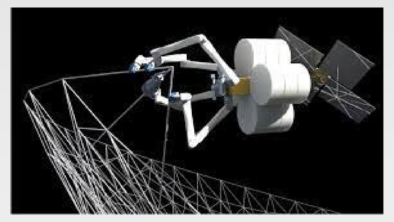
On orbit manufacture of MMOD shields can offer a solution.

Operational Impact: Enhanced resiliency for the space-warfighter and joint force

- MMOD levels continue to increase – compelling threat to DoD and Space Force satellites
- Critical space systems (SBIRS, GPS, DSCS) are required to have high agree of resilience to ensure mission continuity
- Design principles for MMOD protection can be applied to terrestrial warfighting:
  - Ground vehicle protection
  - Ship Hypersonic prevention
  - Body armor

Private Sector Impact: Enhanced resiliency and lifespan of commercial space assets increase economic returns on space economy investments due to higher confidence of long-term success and lifespan of assets, and further develop novel on-orbit manufacturing methods for future economization of the space domain by the private sector. Companies like Made in Space will manufacture large-scale structures on orbit, therefore requiring a higher degree of MMOD risk mitigation.

MADE IN SPACE



Scientific/Engineering Community Impact: The scientific and engineering community can benefit from higher degree of space craft resiliency and maturation of on-orbit manufacturing technology. The proposed technology can help increase the resiliency of:

- NASA human spaceflight missions
- NASA scientific missions
- AFRL scientific missions
- Contribute to the body of hypersonic research

Stakeholders and Subject Matter Experts (SMEs) identified:

Ball Aerospace
AFRL – Space Vehicles Directorate
Collins Aerospace
Made In Space, Inc
Texas A&M University – Hypervelocity Test Lab
Amry Futures Command
Aerospace Corporation
NASA – 3D printing Directorate

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