

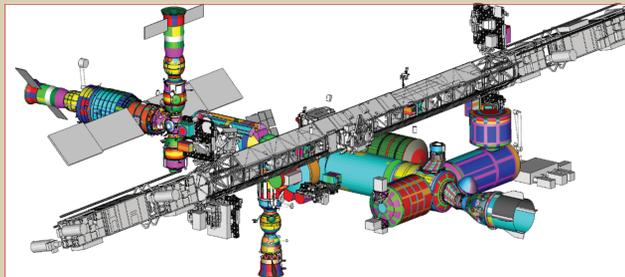
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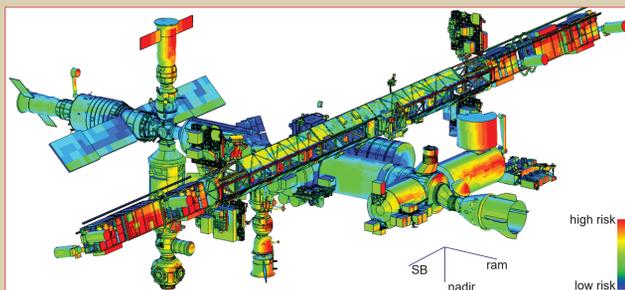
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Introduction

- HVIT's operational objectives for NASA, commercial, and international partners are to 1) help to define MMOD risk requirements 2) provide assessments that identify risk drivers for a specific spacecraft design, and 3) work to design and optimize shielding technologies based on increasing performance and reducing mass.
- The use of Bumper-code underpins all risk assessments provided by HVIT – by using a complete FEM model, Bumper can provide a wholistic view of risk for a given design and mission profile.
- A full risk assessment, however, requires an iterative approach, where Bumper is first used to identify potential risk drivers. Subsequent analysis can focus on iterating the shield design in highest risk areas. And may include the refinement of BLEs through testing, design modification, or reexamination of the failure criteria.
- HVIT utilizes a wide-range of expertise to provide the most accurate risk assessments possible – areas of active research are highlighted below.

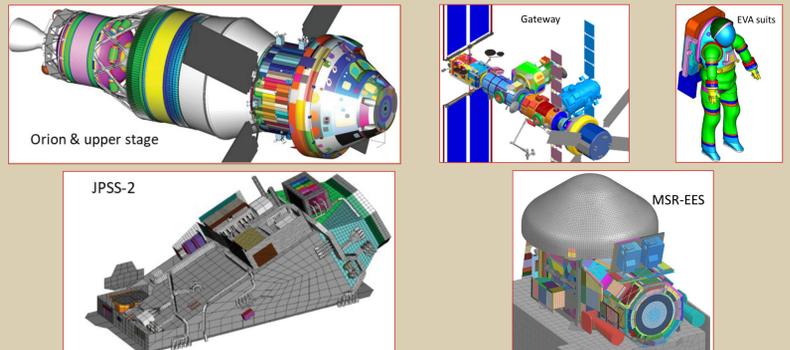


ISS finite element model that is used as an input into Bumper-code during risk assessments. The various colors represent individual property IDs (PIDs) that describe different shield configurations.



Results of a risk assessment shown as a contour plot of relative impact risk for particles >1 mm, where warmer colors represent higher risk areas (generally non-shadowed ram-direction facing) and cooler colors indicate low risk.

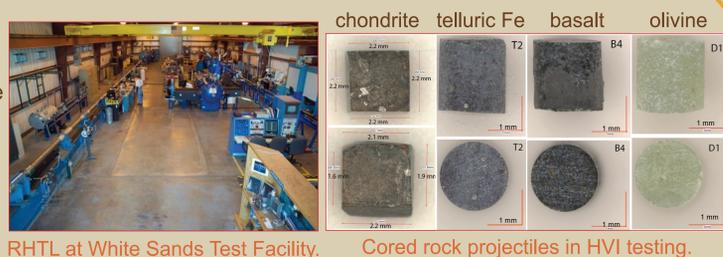
- HVIT supports a diverse range of missions that are both crewed and uncrewed. Some recent highlights include working with Orion, Gateway, space suits development, EVA missions, Mars sample return, James Webb, constellation satellites, and multiple weather satellites.



- Recent accomplishments towards reducing MMOD risk include 1) the implementation of (Nextel/Kevlar) stuffed Whipple shields on the ISS 2) development of multilayer multi-shock shields for inflatable modules 3) refinement of orbital altitude for shuttle, and 4) shield upgrades to Russian Zvezda module.

Hypervelocity testing

- HVIT has the capability to perform impact testing from subsonic to hypervelocity speeds, depending on the needs of the customer.
- Most testing is conducted at NASA White Sands Test Facility (WSTF) Remote Hypervelocity Test Laboratory (RHTL) using two-stage light-gas guns, which can launch projectiles up to ~8 km/s. Higher launch speeds, up to ~10 km/s, are achieved by partnership with the University of Dayton Research Institute (UDRI).
- Recent testing advances include exploring the effect from using meteoritic and natural rock projectile materials on multi-shock shield performance, which will soon be expanded to explore other shield types.

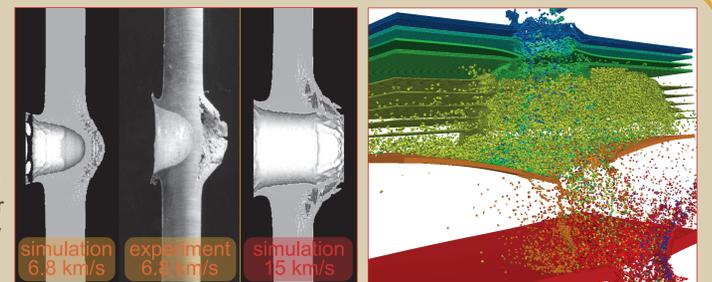


RHTL at White Sands Test Facility. Cored rock projectiles in HVI testing.

- HVIT will design a testing plan according to the expected impact conditions and failure limitations of the shield in question, as well as supervise its execution – including the shipment of all necessary items to remote testing facilities, management of the test series on-site, and the preparation of a post-test report.

Impact simulations

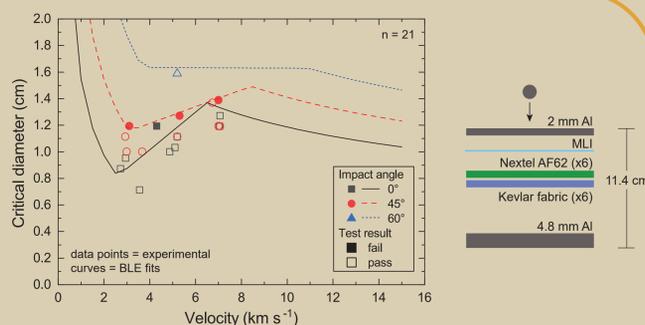
- Hydrodynamic codes (hydrocodes) provide a means of extending the experimental data that is used to build BLEs to speeds that are not physically obtainable in the laboratory environment (>10 km/s).
- Results of hydrocode tests can also be used to bracket expected shield failure for the purpose of designing an economically sound HVI test plan that can be more targeted regarding impact speeds, projectile types, and impact angle.
- HVIT has a variety of commercially available hydrocodes available for use depending on the customers needs, including CTH, Impetus, and EXOS.
- Recent modeling efforts in HVIT are focusing on the influence of projectile shape and tilt angle on the performance of multiple different shield types.



Comparison of CTH simulation (left) to an experimental impact (center) into a 12.7 mm thick Al (1100) plate by a spherical 3.2 mm Al (2017-T4) impactor. Higher velocity impact of same materials on right. Impact simulation of a thermal blanket (cooler colors) overlaying a bumper (orange) and pressure hull (red). Remnant projectile fragments are dark blue in the lower right corner.

Ballistic limit equations

- Any MMOD risk assessment requires each shield used in a FEM (that is not shadowed) to have a defined BLE.
- This equation provides the projectile size, as a function of speed, impact angle, density, and shape, that leads to the failure of a specific shield.
- These equations are the accumulation of thousands of hypervelocity tests, both experimental and hydrocode-based, on different types of shields that vary in material types and standoff distance.
- Recently HVIT is beginning to develop BLEs that incorporate non-spherical projectile shapes into the next iteration of commonly used environmental models



Example BLE for a stuffed Whipple shield on the ISS

- HVIT currently houses 100's of BLEs within Bumper-code for use in risk assessments. Ongoing HVI testing allows for the continual refinement of these equations and the development of new BLEs can be completed if needed.

Post-flight inspections

- Inspections of crewed, uncrewed, and general space-exposed hardware is conducted whenever possible by HVIT personnel.
- During these inspections, impact features are visually identified using magnifying lenses, photos are then collected, measurements of diameter and depth are recorded, and in some cases, in-tact core samples are removed.
- Extracted samples are subjected to an elemental analysis focused near the bottom of the crater to aid in determining the provenance of the impactor (either micrometeoroid or orbital debris).



Aggregation of impact locations from the first 20 Space-X flights. Example images of impact damage.

- Post-flight data, such as the number of recorded impact events and the origin of the impactor, offer a crucial comparison to the predicted impactor flux provided by environmental models such as MEM 3 and ORDEM 3.2, and also be used by NASA to augment existing MMOD shielding for ongoing missions where necessary.

Conclusions/forward work

- HVIT uses a multi-pronged approach (experimental HVI, hydrocode simulation, and Bumper analysis) to provide robust risk assessments all types spacecraft/flight hardware for NASA, commercial, and international partners.

Areas of continuing development for HVIT include:

- Integration of impact sensors into shield designs for real-time impactor flux data.
- Continued development of lower-mass shielding designs with increased protection capabilities.
- Research on self-healing materials, the reduction of ejecta particles, and integrating shield elements into other flight critical systems (radiators, solar, etc.).