The Hypervelocity Impact Technology (HVIT) office at the National Aeronautical and Space Administration (NASA) Johnson Space Center (JSC) is dedicated to support NASA flight programs in meeting their meteoroid and orbital debris (MMOD) protection requirements both efficiently and effectively, with a minimum of shielding mass, volume, and cost. This paper provides an overview of HVIT capabilities in providing hypervelocity tests, analyses, MMOD risk assessments and shielding expertise. HVIT personnel work closely with NASA program and safety/mission assurance personnel to develop program-specific MMOD protection requirements which are both achievable based on initial risk assessments and will meet overall safety and mission success requirements. HVIT then proceeds with hypervelocity impact testing and hydrocode assessments to update and verify ballistic limit equations used in the MMOD risk assessment. Hypervelocity impact tests are primarily performed at the NASA WSTF Remote Hypervelocity Test Laboratory (RHTL). Other hypervelocity facilities that provide complementary test capabilities are called on when necessary to fill data gaps. The goal of the final pre-flight MMOD risk assessment is to show compliance with MMOD requirements prior to flight. This final assessment will also incorporate changes in the MMOD environment from meteoroid showers and orbital debris breakups. After the mission is flown, post-flight inspections are performed by HVIT to document and trend MMOD damage to returned spacecraft surfaces and hardware. HVIT accomplishments in NASA mission support are described. In addition, current HVIT activities to aid ongoing NASA crewed missions and science missions are presented.

1 Introduction

The NASA Hypervelocity Impact Technology (HVIT) team is the agency leader in engineering and operational solutions to protect spacecraft from micrometeoroid and orbital debris (MMOD). HVIT personnel have been involved since the mid-1980s in assessing MMOD risk to NASA spacecraft based on the results of hypervelocity impact tests and analysis [1] [2]. HVIT predicts MMOD risks to spacecraft, collaborates with spacecraft teams to optimize shielding and mission designs to minimize risk, assists spacecraft programs in defining MMOD risk requirements, and develops new shielding technologies and concepts. Hypervelocity impact testing, computer simulations and damage equation development form the foundation of the HVIT analytical suite, which along with decades of practical mission experience, contribute to crew safety and mission success. HVIT services and products are not limited to NASA and US Government organizations, but also serve the private spacecraft sector and other space agencies.
2 MMOD Risk Assessments

Over the past 30 years, HVIT has provided MMOD risk assessments for all NASA crewed and numerous non-crewed spacecraft with missions in low-Earth orbit (LEO) and deep space. These assessments identify areas of a spacecraft that are predicted to be more vulnerable to MMOD impacts and require more protection than other areas, as well as identify vehicle regions that drive overall mission MMOD risk. The “risk drivers” identified by these risk assessments are the focus of subsequent analysis and testing, to confirm the basis and reasonableness of the assessment. The HVIT team has the capability to rapidly produce finite element models (FEMs) of spacecraft that are compatible with HVIT’s risk-analysis tools, the primary tool being the Bumper assessment code [3] [4]. Figure 1 illustrates the MMOD risk assessment process.

![MMOD risk assessment process based on Bumper-code, tests and analysis to identify and mitigate high MMOD risk areas of the spacecraft to meet MMOD protection requirements.](image)

**Fig. 1.** MMOD risk assessment process based on Bumper-code, tests and analysis to identify and mitigate high MMOD risk areas of the spacecraft to meet MMOD protection requirements.

Figure 2 provides an example FEM that HVIT uses to assess MMOD penetration risks for the International Space Station (ISS) where penetration is defined as failure of the crew module pressure shell by either complete penetration (perforation), detached spall from the inside surface of the pressure shell or through cracks. In addition, the ISS penetration assessment includes failure of external stored energy devices, including pressurized propellant-, coolant- and gas-storage tanks, as well as control moment gyros. Each color in the FEM in Fig. 2 represents a different MMOD shield type or region (referred to in Bumper-code as a property identifier or PID) which can vary in number of layers, thickness of layers, spacing between layers, materials of construction and failure criteria. There are hundreds of different shield PIDs that are represented in the ISS FEM. Hypervelocity impact tests and analysis are performed for each unique spacecraft PID to derive ballistic limit equations (BLEs) which define the MMOD particle size that will be on the threshold of failure for a given PID region as a function of impact velocity, angle and MMOD particle density. The MMOD penetration risk is assessed in Bumper-code by determining the number of MMOD impacts that would exceed the BLE particle size partitioned into different velocity, angle and density bins for each region using NASA’s meteoroid and orbital debris environment models: Meteoroid Engineering Model (MEM) and Orbital Debris Engineering Model (ORDEM). Currently, MEM 3 and ORDEM 3.2 are the latest NASA meteoroid and orbital debris models used in HVIT MMOD risk assessments [5] [6]. A HVIT risk analyst will first develop the FEM to use in the Bumper-code assessment based on computer-aided design (CAD) solid models of the spacecraft.
The HVIT analyst will work with the spacecraft program to determine failure criteria for each FEM PID, assign appropriate BLEs for each PID and will perform initial MMOD assessments to identify MMOD risk drivers that control the MMOD risk. HVIT test engineers will perform impact tests and analysis on representative samples of the spacecraft with an emphasis on risk drivers as well as any areas where the initial BLEs assigned to the PID are uncertain, to update the BLEs used in the MMOD risk assessment. These BLEs are transferred into Bumper code and used in subsequent MMOD risk assessments to further refine the risk analysis. One of the computational tasks performed by Bumper-code is to determine the amount of shadowing of the MMOD environment for each element in each PID by all the other elements in the FEM. Figure 3 shows the results of the Bumper shadowing algorithm, where areas with more predicted MMOD impacts are colored red and less/more-shadowed regions colored blue. For ISS and any LEO spacecraft, far more MMOD impact damage will occur on the forward pointing (velocity-direction) area of the spacecraft, and less on the aft and nadir (Earth-facing) directions [3, section 2.8]. The high- and medium-impact risk areas on ISS have more robust MMOD shields compared to the low-impact risk areas [2] [7]. ISS MMOD penetrations resulting in perforation and atmospheric leak from the crew modules have not occurred, but if a penetration was to happen, the crew and ISS survivability could be at risk. Another MMOD risk assessment tool applied by HVIT to large, crewed spacecraft such as ISS and the Gateway lunar-orbit station, is the Monte-Carlo Spacecraft Crew Survivability (MSCSurv) code [8]. This risk assessment code goes beyond calculating penetration chances and assesses internal consequences of penetration to determine the risk for loss-of-crew and the possibility that crew would have to evacuate the station (ISS or Gateway) if an MMOD penetration were to occur.
Fig. 3. ISS MMOD impact risk contour plot (for 1mm and larger MMOD), red = high impact risk, green = medium impact risk, blue = low impact risk.

2.1 Recent HVIT Activities

HVIT supports NASA and commercial crewed missions with MMOD risk assessments, hypervelocity impact testing and impact simulations including ISS, Orion, Human Landing Systems (HLS), Space Launch System (SLS) upper stages, Gateway station, LEO crew transfer vehicles, Extravehicular Activity (EVA) space suits, LEO commercial space stations and commercial human missions. HVIT provides similar support for non-crewed satellite programs including the Mars Sample Return (MSR) spacecraft that will shepherd Martian soil samples to Earth via the Earth Entry System (EES), constellation satellites, various Earth observation and weather satellites (Joint Polar Satellite System-1 and -2, Landsat 9), and space telescopes (James Webb Space Telescope). FEMs used in some of these assessments are shown in Fig. 4.

Fig. 4. Finite Element Models used in HVIT MMOD Risk Assessments.
2.2 Major HVIT Accomplishments

HVIT personnel have developed several innovative techniques that have been implemented to reduce MMOD risk, increase flight safety and mission success for NASA spacecraft. Some of the more important improvements are listed below.

- Nextel/Kevlar stuffed Whipple shields were developed and patented by HVIT personnel and have been used extensively to protect ISS NASA and international partner modules and commercial cargo vehicles from MMOD impacts [9] [10].

- Advanced multilayer shielding developed by HVIT have been applied to spacecraft MMOD protection such as Stardust and the Fermi Gamma-ray Space Telescope as well as inflatable modules [11] [12]. These shields are often referred to as flexible multi-shock shields.

- Operational methods were implemented to reduce risk to the thermal protection system (TPS) and thrusters of re-entry vehicles via on-orbit inspection of these critical areas that are necessary for successful return (i.e., areas where MMOD damage can remain unrecognized until atmospheric entry with potential catastrophic consequences if this step is not taken), with repair or safe-haven to mitigate risk if critical damage is found. This operational technique is being performed for all re-entry vehicles (crew and cargo, NASA and international) that dock or berth to ISS. HVIT played a leading role in developing the technical rationale for this procedure, and successfully championed this modification through the program change system.

- Another operational technique to reduce MMOD risk that has been implemented with many flight programs is adjusting the flight attitude of the spacecraft to reduce MMOD risk while still meeting mission objectives. This method was implemented for the first time in the Shuttle Program during free-flight portions of the mission and was extended while the Shuttle vehicle was docked to ISS after Space Transportation System-121 (STS-121) [3, section 2.8]. HVIT analysis results provided the foundation for making these operational adjustments.

- Major MMOD shielding upgrades were made to existing Russian elements to ISS based on cooperative work between HVIT and Russian counterparts. For instance, 28 panels were added to the exterior of the Zvezda Service Module (SM) by EVA crew in the early 2000’s to reduce MMOD risk by nearly a factor of 2. Figure 5 illustrates some of the 23 panels added to the conical region between the small and large diameter regions of the Zvezda SM, and another 5 panels were installed at the forward end of the small diameter cylinder. The panels consisted of an outer aluminum sheet followed directly by a corrugated aluminum sheet, then a 10cm gap to a rear composite panel that combined Russian “technical cloth” which is equivalent to Kevlar™ that was attached to a fiberglass layer. The augmentation panels were installed over the existing Whipple shield providing a robust solution to reducing MMOD risk and resembled a stuffed Whipple shield. Another success was the standoff shielding added to the Soyuz vehicle Orbital Module (OM) (Fig. 6) in 2012 starting with 60S, and Progress Cargo Module (CM) with 47P. Previously to this change, these areas were only protected by a conformal thermal blanket, while these modifications reduced MMOD risk by a factor of 2 to 3, depending on the vehicle and dock location.
Fig. 5. Russian Zvezda Service Module augmentation shields added by EVA (left image shows an EVA crew during installation, on right is an image of several of the 23 panels added by EVA).

Fig. 6. Soyuz vehicle Orbital Module MMOD enhancement consists of a 1mm thick aluminum bumper installed 15mm from the pressure shell and a thermal blanket installed on top.

3 Hypervelocity Impact Testing

HVIT performs hundreds of tests each year on two-stage light-gas gun (LGG) launchers up to nearly 8 km/s at the NASA White Sands Test Facility (WSTF) Remote Hypervelocity Test Laboratory (RHTL) (Fig. 7). Tests up to 10 km/s are supported by the three-stage LGG at the University of Dayton Research Institute (UDRI). The data from these tests are used to update ballistic limit equations and to compare to hydrocode simulation results. Test data is also maintained in a HVIT database of past tests. HVIT provides the following customer-oriented test support:

- Test planning based on analysis results for expected MMOD impact conditions near the failure limit of the target, i.e., projectile size, impact velocity, angle, and projectile density.
- Test matrix developed to minimize test costs, planning/conducting test readiness reviews, preparing pre-test documents.
- Test article/fixture build which are shipped along with projectiles and instructions as required by the test facility for all tests.
- Monitoring tests at the test facility and adjusting the test plan as required to meet objectives of the tests.
- Documenting damage and reporting the results of the tests.
Recent testing is exploring the effect from using meteoritic and natural meteoroid-like projectile materials on shield performance. These projectile materials may be more suitable for testing where the flux of meteoroid impacts would be expected to dominate over orbital debris (for example, Gateway lunar station, cis-lunar and deep-space missions). To this end, successful tests have been conducted using cylindrical projectiles made of ordinary chondrite, as well as other terrestrial analog materials such as dunite, basalt, and telluric iron into a shield layup that will be used for the MSR micrometeoroid garage that will protect the Earth entry vehicle during its return flight (Fig. 8).

Fig. 7. Left: WSTF two-stage light-gas gun launchers (0.17cal and 0.50cal ranges on right, and 1” range left). Right: High-speed image of plasma and ejecta produced by hypervelocity impact.

Fig. 8. Cylindrical lithic (rock-like) projectiles used in recent testing.

4 Hypervelocity Impact Computer Simulations

HVIT uses specialized computer programs called “hydrocodes” to simulate how spacecraft shielding may respond to a hypervelocity impact before actually testing the spacecraft hardware. In this way, HVIT can tailor a test plan to save time and reduce costs. Additionally, hydrocodes can be used to estimate
spacecraft shielding performance in conditions that are beyond current impact technology capabilities, such as at extremely high velocities above 10 km/second. Hydrocodes currently in use at HVIT include CTH, Impetus, and EXOS. Figure 9 shows an example of a CTH simulation compared to experiment.

![CTH Sim (6.8 km/s), Test (6.8 km/s), CTH Sim (15 km/s)](image)

Fig. 9. CTH simulation on left, experimental result in middle, for 0.32cm aluminum (2017-T4) spherical projectile impact at 6.8 km/s and normal to the 1.27cm thick aluminum (1100) target. CTH simulation for same impactor at 15 km/s on right shows predicted damage growth to a through-hole (perforation).

5 Ballistic Limit Equations

MMOD risk assessments require that each shield type on a spacecraft be assigned a ballistic limit equation (BLE) to describe the particle size that would cause the shield to fail as a function of MMOD impact velocity, angle, density, and shape [3] [13]. Small spacecraft may have only a few dozen BLEs, whereas larger spacecraft may have hundreds. Results from thousands of tests and hydrocode runs have been methodically analyzed to create an extensive catalog of BLEs for a wide variety of surface materials and shielding configurations. HVIT is developing on BLEs that incorporate projectile shape effects to support the eventual release of the next generation orbital debris environment model [14]. The HVIT team continues to expand the BLE catalog as new spacecraft and shielding technologies emerge. Figure 10 provides an example BLE.
Post-Flight MMOD Inspections

HVIT performs inspections of crew and cargo return vehicles and other returned hardware after flight to provide data used to trend MMOD damage, update MMOD environment models and quantify spacecraft design margins. Figure 11 illustrates an example MMOD impact damage identified on the SpaceX ISS cargo vehicle. Samples of the largest damage are analyzed by Scanning Electron Microscope/Energy Dispersive X-ray Analysis (SEM/EDXA) to determine source of the damage (meteoroids versus orbital debris). Post-flight MMOD damage can be used by NASA programs to justify additional MMOD protection if and where needed to reduce loss-of-mission risk. For instance, Shuttle radiators and wing leading edge were augmented based on HVIT post-flight inspection findings [13, section 1.3]. These modifications were successful at least on one occasion in preventing MMOD impact from causing a radiator leak during the STS-128 mission that would have resulted in early mission termination [15].

Concluding remarks and future directions

HVIT has been successful at improving MMOD protection of NASA spacecraft to meet/exceed crew safety and mission success requirements. This effort has been based on risk assessment and computer
simulation tools that are well-grounded in hypervelocity impact test data. HVIT future efforts are in the following areas:

- Continue to develop lower mass shielding with better MMOD protection performance that incorporates multifunctional features, includes self-healing and/or easy to repair materials, and identify materials/configurations to reduce secondary ejecta fragments that pollute the space environment. Multifunctional shielding will combine MMOD protection with other required spacecraft systems such as radiation shielding, thermal control, solar power generation, etc.
- Integrate impact detection/location sensors into MMOD shielding and vehicle TPS.
- Improve hypervelocity testing and computer simulation capability to use in developing and verifying ballistic limit equations.
- Continue efforts to evaluate failure criteria and model failure limits for stored energy systems (pressure vessels and batteries).

8 References