

The 13<sup>th</sup> Hypervelocity Impact Symposium**ORBITAL DEBRIS ASSESMENT TESING IN THE AEDC RANGE G**Marshall Polk<sup>1</sup>, David Woods<sup>2</sup>, Brian Roebuck<sup>3</sup>, John Opiela<sup>4</sup>, Patti Sheaffer<sup>5</sup>, and J.C. Liou<sup>6</sup>*1*Arnold Engineering Development Complex (Arnold AFB, TN 37389, [edward.polk.1@us.af.mil](mailto:edward.polk.1@us.af.mil))*2*Arnold Engineering Development Complex (Arnold AFB, TN 37389, [david.woods.ctr@us.af.mil](mailto:david.woods.ctr@us.af.mil))*3*Arnold Engineering Development Complex (Arnold AFB, TN 37389, [brian.roebuck.ctr@us.af.mil](mailto:brian.roebuck.ctr@us.af.mil))*4*Jacobs Technology (NASA Johnson Space Center, TX 77058, [john.n.opiela@nasa.gov](mailto:john.n.opiela@nasa.gov))*5*The Aerospace Corporation (El Segundo, CA 90245, [Patti.M.Sheaffer@aero.org](mailto:Patti.M.Sheaffer@aero.org))*6*NASA Orbital Debris Program Office (NASA Johnson Space Center, TX 77058, [jer-chyi.liou-1@nasa.gov](mailto:jer-chyi.liou-1@nasa.gov))

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**Abstract**

The space environment presents many hazards for satellites and spacecraft. One of the major hazards is hypervelocity impacts from uncontrolled man-made space debris. Arnold Engineering Development Complex (AEDC), The National Aeronautics and Space Administration (NASA), The United States Air Force Space and Missile Systems Center (SMC), the University of Florida, and The Aerospace Corporation configured a large ballistic range to perform a series of hypervelocity destructive impact tests in order to better understand the effects of space collisions. The test utilized AEDC's Range G light gas launcher, which is capable of firing projectiles up to 7 km/s. A non-functional full-scale representation of a modern satellite called the Debrisat was destroyed in the enclosed range environment. Several modifications to the range facility were made to ensure quality data was obtained from the impact events. The facility modifications were intended to provide a high impact energy to target mass ratio (>200 J/g), a non-damaging method of debris collection, and an instrumentation suite capable of providing information on the physics of the entire impact event.

**Keywords:** Orbital Debris; Light Gas Gun; AEDC Range G; Hypervelocity Impact; Iridium 33; Kosmos-2251, Debrisat, High Speed Video, Low Earth Orbit Collision Testing, Fengyun-1C weather satellite, Soft Catch, Debris Recovery, Arnold Engineering Development Complex

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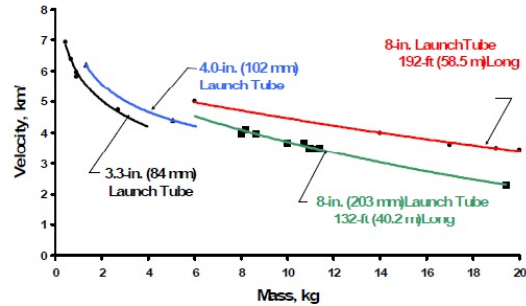
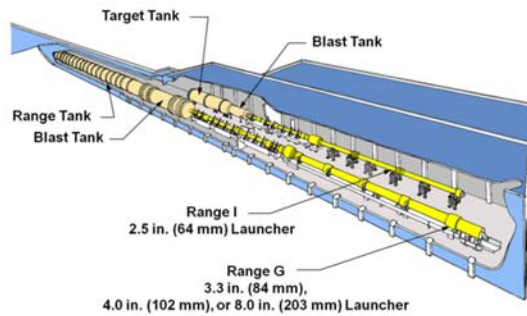
**1. Program Overview**

The goal of the Debrisat project was to characterize fragments generated by a hypervelocity collision involving a modern satellite in low Earth orbit (LEO). The breakup models used by DoD and NASA before the Debrisat program were partially based on a previous impact test program in the AEDC's Range G facility. This previous test program impacted targets that were representative of 1960's era satellite technology. Collisions involving modern satellites such as Iridium 33 and Fengyun-1C indicated discrepancies between model predictions and the observed data. The Debrisat program was thus created to resolve these discrepancies. At the heart of the program is the Debrisat test article which is an engineering model representing a modern, 60-cm/50-kg class LEO satellite. Through a high energy laboratory-based hypervelocity impact, the satellite would be catastrophically fragmented with all substantial particles being collected for further analysis. Characterization of the properties of breakup fragments down to 2 mm in size would be later performed from the collected debris. The data obtained, including fragment size, area-to-mass ratio, density, shape, material composition, optical properties, and radar cross-section distributions, would then be used to supplement the DoD's and NASA's satellite breakup models to better describe the breakup outcome of a modern satellite. [1]

**1.1. G-Range Facility Information**

The Range G launcher is a two-stage, light-gas gun that is capable of launching various types of projectiles at velocities up to 7 km/s. The facility is routinely launches projectiles at velocities between 3-6 km/s. Projectiles up to 203 mm (8.0-inch) diameter are launched into a 3-m (10-feet) diameter, 283.5-m (930-feet) long instrumented tank that can be maintained at pressures from 0.2 torr to 1.7 atmospheres. The launcher started test operations in 1962 at 63.5mm diameter but has been

significantly upgraded over the years to launch larger masses at high velocities and lower peak acceleration loads. Currently the facility has three sizes of interchangeable barrels: 84 mm (3.3in), 102 mm (4in), 203 mm (8in).



(a) (b)

Fig. 1. Range G Light Gas Launcher (a) Facility Schematic of Range G and Range I (b) Range G Operating Envelope

Range G is a unique light gas launcher not only because of its size but because of its capability to launch large objects with minimal acceleration loads (G's). In 1994 the launcher was upgraded to the current 84mm barrel configuration. This upgrade was a clean sheet design upgrade to the entire launcher that increased the pumping capacity of light gas in the compression cycle. This allows the facility to reduce peak acceleration loads by lengthening the barrel and spreading the load over a longer distance. This launch capability gave AEDC the capability to accelerate projectiles with complex geometries that would have often failed in the earlier 63.5mm configuration.

## 1.2. Previous Test Programs

In 1992 AEDC helped to provide critical impact data in the Satellite Orbital Debris Characterization Impact Test (SOCIT). This was the test program that provided key data to the DoD and NASA satellite breakup models for on-orbit collisions. During this program AEDC performed high energy impact tests using a surplus flight-ready Navy transit navigation satellite, a solar panel, and an interstage adapter. All of this hardware was surplus material that had been fabricated in the 1960's. The satellite itself was 46 cm diameter by 30 cm height and weighed 34.5 kg. The 63.5mm diameter launcher in Range G was used to fire a 150g solid aluminum sphere into the satellite at 6.1 km/s providing 78 J/g impact energy to target mass ratio. [2]

The SOCIT program was mutually beneficial to AEDC, DoD, and NASA. DoD and NASA obtained data for their breakup models and AEDC acquired important information about debris collection materials and how they could be better used in the facility impact chamber. These collection systems are often referred to as “soft catch” due to their ability to capture debris particles with minimal change to the initial impacting shape. SOCIT chose to use polyurethane foam [3] with densities of 60 kg/m<sup>3</sup>, 96 kg/m<sup>3</sup> and 192 kg/m<sup>3</sup>. The layers of foam were attached to rigid plywood backing that is then affixed to the inside of the range tank. The foam is configured so that the first layers are low density; either 60 kg/m<sup>3</sup> or 96 kg/m<sup>3</sup>, and the final layers are constructed of the 192 kg/m<sup>3</sup> foam. This dual density design reduces overall penetration depth and also reduces debris deformation. Slow debris is captured in the initial layers of low density foam and debris traveling at high velocity is captured in the layers of dense foam.



Fig 2. SOCIT Test Article with Multilayer Foam Soft Catch

The SOCIT test also helped determine a standard suite of instrumentation that should be fielded for high energy orbital debris test programs. The standard facility photography equipment (laser light still cameras and high speed video cameras) is not always capable of providing insight into the actual impact occurrence due to impact flash and lingering plasma/gas cloud. Instead, high power x-rays systems are often recommended to evaluate the debris field immediately after impact. Other instruments such as radiometers and spectrometers are recommended to provide information about the impact flash and the constituents of the gas/plasma cloud.

## 2. Facility Modifications for DebrisSat Orbital Debris Assessment Program

The main objectives presented to AEDC at the beginning of the program were to provide the maximum possible impact energy into the test article based on the launcher capability and to also provide a collection system capable of capturing 90% of the debris fragments. AEDC and NASA jointly developed a facility configuration based on the operating envelope of the launcher shown in figure 1 and AEDC experience with debris collection systems. The general program requirements are presented in the list below.

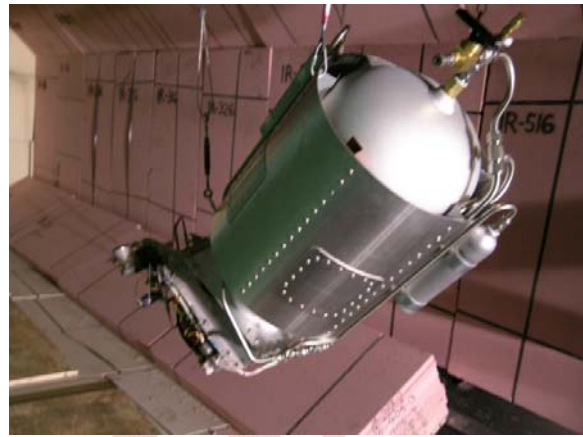
- Targets: Scaled Multi-Shock Shield, DebrisLV, and DebrisSat
- Approximately 500-600 g hollow aluminum and nylon projectile
- 7 km/sec (+/- .1 km/s) projectile velocity
- Test chamber pressure less than 267 Pa (2 torr).
- A fragmentation soft catch system based on low density foam material that shall be used to collect the resulting impact debris field.

The test team chose to perform three impact experiments of which two utilized the soft catch collection system. The first test was a checkout shot to ensure the 7.0 km/s velocity could be attained from the Range G launcher with a modified projectile configuration. This test utilized a NASA supplied 5x scaled version of a multi-shock shield constructed by the Hypervelocity Impact Technology (HVIT) Group at NASA Johnson Space Center with no soft catch (figure 3a). [4] The second test was a full facility checkout shot using a low cost test article named DebrisLV (figure 3b). This test was a 15kg representation of the upper stage from a launch vehicle that was fabricated by The Aerospace Corporation. The third and final test was the critical data shot that utilized the DebrisSat satellite. The DebrisSat was a 56 kg full scale replica of a modern day LEO satellite with solar panels and multi-layer insulation. DebrisSat's internal components were structurally similar to real flight hardware but were non-functional. The replica DebrisSat also lacked live battery packs (simulated battery packs were installed) due to battery material safety concerns.

For all three tests AEDC provided the standard suit of instrumentation which includes six high speed phantom cameras, 2 laser lit still cameras, and six X-ray still images for the projectile flight analysis and two x-ray imaging systems for the target. Radiometers, spectrometers, and custom made witness plates were supplied by The Aerospace Corporation who also operated the instruments. A full listing of instrumentation is provided in Appendix A.



(a)



(b)

Fig. 3. Test Articles (a) Shock Shield (b) DebrisLV

## 2.1. Gun Cycle

The Range G launcher was configured with 39.6 m of 84 mm diameter launch tube to reach the maximum facility rated velocity of 7 km/s. This velocity is the upper limit of the Range-G operating curve and requires minimization of the projectile mass and a careful design of the gun configuration. Prior to the DebrisSat program AEDC had launched projectiles weighing approximately 450 grams at 6.94 km/s. An analysis was performed on the previous gun configuration and a new operating cycle was selected based on a preliminary projectile weight of 500-600 grams. A very high acceleration load was imposed on the projectile in order to reach 7km/s target velocity. Peak instantaneous acceleration ended up being just under 87,000 G's, which is 20,000-50,000 G's greater than the typical AEDC 3-6 km/s launch cycle.

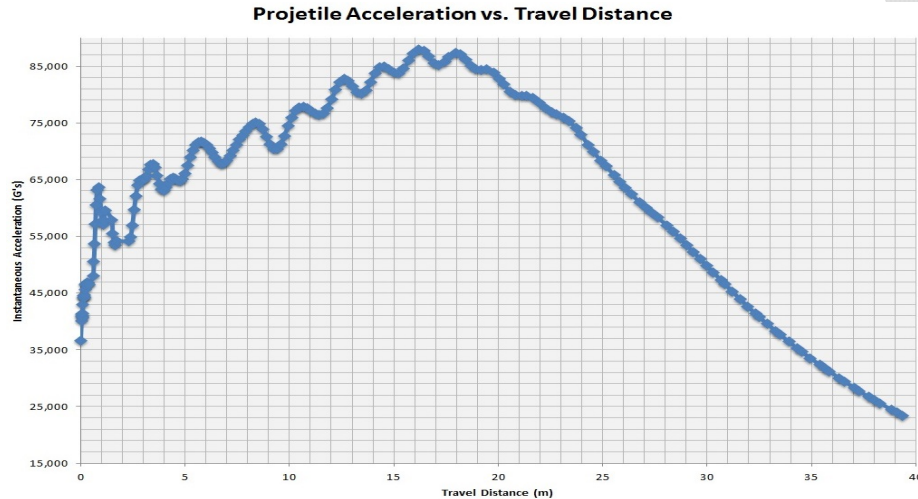


Fig. 4. Projectile Acceleration vs. Distance Traveled Down Barrel

Actual muzzle velocity ended up being slightly less than the 7.0 km/s value predicted by computer simulation. The facility uses two continuous wave x-ray detectors at a known distance apart to accurately calculate the velocity of the projectile just beyond the muzzle of the barrel. The velocity values as measured by this system are shown in table 1. The measured velocity in Range G is normally within 1-2% of the computer predicted values. The first two launches were within the standard range operating tolerance, but the final launch appears to be either an anomaly or an intermittent effect from minor complications with the projectile.

Table 1. Measured Projectile Velocity & Mass

| Test      | Velocity (km/s) | Mass (g) |
|-----------|-----------------|----------|
| Checkout  | 6.91            | 598      |
| DebrisLV  | 6.91            | 598      |
| DebrisSat | 6.79            | 570      |

Operating the Range G launcher at the edge of the envelope did generate concerns about the projectile survivability and launcher wear. The past experience operating the Range G launcher at a high acceleration conditions indicates that certain areas of the launch system do experience higher than normal wear. Inspection tools such as video bore scopes, laser bore scanners, and physical bore measurement gauges were used to quantify the launcher condition in between each of the tests. The inspection results showed that the launcher was experiencing slightly higher than normal wear, but the wear was less than what was observed during the last test program with a 7.0 km/s muzzle velocity objective. While the DebrisSat program only had three data points, it would be logical to assume that the configuration could perform a greater number of launches without major wear concerns to the facility.

## 2.2. Projectile

The projectile was based on a successful design from a previous AEDC hypervelocity impact program. The design used a hollow aluminum cylinder made of 7075-T651 with a nylon sleeve. The aluminum cylinder is coated with a light layer of RTV to prevent gas intrusion and then threaded into the nylon sleeve. The nylon sleeve provides a soft interface to the launcher bore while still maintaining the ability to provide a proper gas seal. An aluminum cap is then threaded into the front of the



sleeve to provide a flat face for impact. Unlike a sphere/sabot projectile design as used in the SOCIT test series, this configuration allows the entire projectile mass and resultant kinetic energy to be transferred into the target.

The previous design of this projectile was a 1000g version that was successfully launched at velocities ranging from 4-6 km/s. The lower launch velocity allowed this projectile to be designed with a significant margin of safety. It easily survived the mechanical loads imposed by the gun launch. Compromising the design strength in order to reach the 400-500g weight reduction required for the DebrisSat program was a major concern for the designers. All structural changes were analyzed in the ABAQUS explicit finite element analysis (FEA) software using input load conditions from the AEDC light gas gun simulation program. It was found that weight could be reduced by increasing the outside and inside diameter of the aluminum insert which effectively enlarged the internal void. The total length of the assembly could also be shortened without encountering stability problems both in the gun bore and also in free flight.

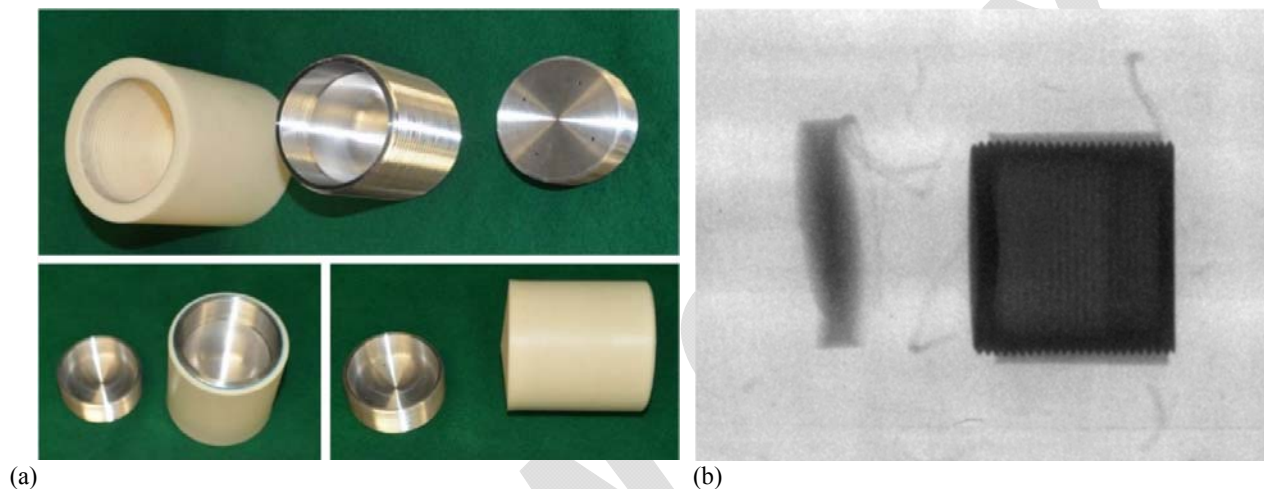


Fig. 5. DebrisSat Projectile (a) Assembly Pictures (b) In-flight X-Ray of Aft End Failure

During each test the projectile was able to successfully impart the total muzzle energy into each target, but unfortunately the design changes created a mechanical failure in the aft part of the assembly. Increasing the diameter of the aluminum reduced the surface area that connected the solid flat base of the nylon to the portion containing the threads. This area reduction weakened the model structure. However, the area reduction alone was not enough to cause a failure. The Range G launcher also has a taper of the bore diameter that increases towards the muzzle exit. This taper is used to account for the normal material erosion on the outside of the projectile. The high velocity required for DebrisSat coupled with a large taper in the barrel assembly may have contributed to partial projectile failure during launch. Additional finite element simulations were performed after the test program using as measured projectile and launcher geometry. These simulations showed that the gun taper was the likely cause of the rear separation due to model wear being less than anticipated. These types of failures are extremely rare in the standard operating velocity of Range G as the wear and launcher taper have been properly matched. This single program failure mode indicates that further evaluation of the internal ballistics may be necessary to define taper rates and model performance during high velocity launches. Regardless, the separation of the aft nylon part of the projectile did not affect the planned catastrophic outcome of the impact. The objectives of the DebrisLV and DebrisSat impact tests were successfully met.

### 2.3. Soft Catch

After the SOCIT program AEDC continued to perform studies to evaluate different materials capable of capturing high velocity fragmentation particles. Experiments with a wide variety of materials showed that good data could be obtained with low cost bundles of ceiling tile, but the layered foam of varying density used on SOCIT was the best solution to collect small and large debris particles at varying velocities. [5] [6] The foam design was a more costly option but it was selected for the DebrisSat program since fidelity of capture debris was a program requirement. Only two significant changes were made to the foam design between the SOCIT program and the DebrisSat program.

The first change was a new octagonal system that was developed for the 10ft inside diameter AEDC range tank. This geometry allowed more spacing between the impact point and the front face of the foam panels. The geometry configuration reduces foam damage from the impact blast wave and also allows the debris cloud to expand slightly further thus potentially reducing

the mass that is impacting a single piece of foam. The octagon shape is also configured to provide a nearly equidistant distance path from the test article which allows for a better characterization of the debris field.

The second change was a modification to the foam density gradient. The DebrisSat panels provided an improved density gradient by adding more low-density outer layers and using three differing foam densities per panel instead of just two as were used on SOCIT. The AEDC studies after the SOCIT program showed that a mixture of low density and high density foam was not ideal for high speed debris fragments. The low density foam often did not reduce the speed of the debris sufficiently and in turn the debris would penetrate the remaining layers of high density foam and impact the rigid plywood backing. Increasing the density of the outer layer to slow the larger debris would in turn deform some of the smaller pieces of debris. 48 kg/m<sup>3</sup>, 96 kg/m<sup>3</sup> and 193 kg/m<sup>3</sup> density foam was selected for use on all soft catch panels. The foam boards were all pre-cut to dimensions of 2 ft. x 4 ft., carefully stacked in the density gradient, and bound to plywood backing using common nylon banding straps. Simple strapping was favored over adhesives as it would be very easy to separate the layers for analysis after the test. After strapping, each panel's front, rear, and layers were marked with a unique ID code. Down-range panels, expected to absorb the most debris, were twice the thickness of the side and up-range panels, with much more low-density material. The layer configuration for each type panel can be found in Appendix B.

The "soft-catch arena" inside the test chamber was constructed in the same fashion as the SOCIT test. The panels were attached to the chamber (wall/floor/ceiling) in a roughly octagonal pattern by use of sliding tracks. Panels composing the down-range end of the arena were stacked on each other and held upright by a backstop of plywood on angle iron supports. The up-range "lips" were attached using angle iron. The overall length of the soft-catch arena was selected to allow the debris cloud to expand to at least the size of the downrange wall. This would spread the energy and improve survival of the downrange panels.

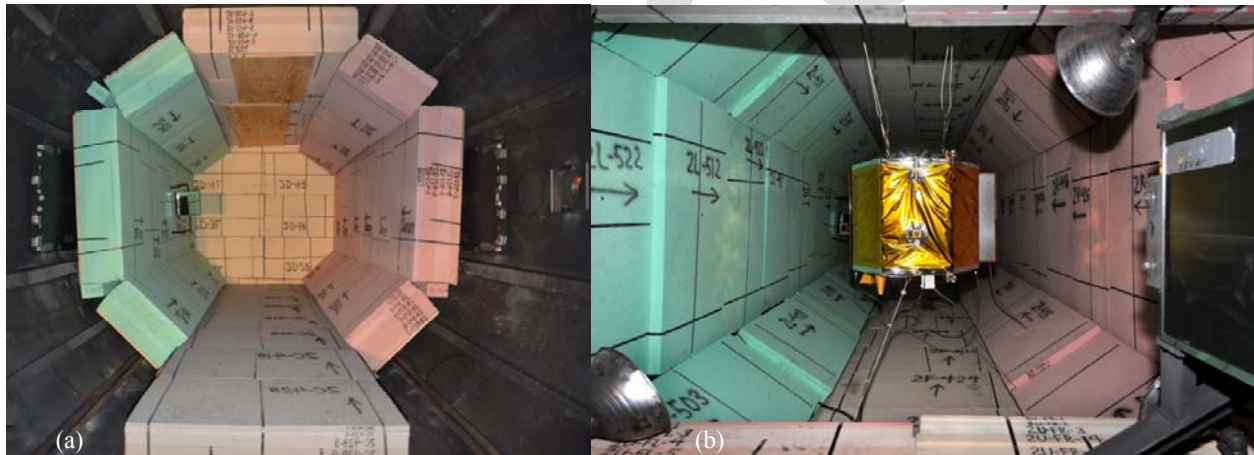


Fig. 6. DebrisSat Soft Catch (a) Assembly Pictures (b) Completed Structure with DebrisSat Satellite and Front Panels

Posttest analysis indicates that some of the foam used for the soft catch did vaporize during the test and then re-solidified on some of the surrounding surfaces. The plasma generated from the impact pyrolytically ablated the exposed surfaces on many of the surrounding foam blocks. The ablated foam products were carried along with the plasma and then deposited on any nearby surfaces. Witness plates were present on all three launches. On both of the impacts with the soft catch system, the witness plates were found to be contaminated with a film of condensed foam. Recovered debris fragments did not appear to be coated by any condensed foam residue. Deposition of target/projectile materials on ancillary surfaces is not an uncommon occurrence in the range, but materials generated from the impact are often deposited on surfaces located in the line of sight from the impact point. The foam contamination was found to have affected all exposed surfaces of the witness plates including the surfaces facing away and shielded from the impact event. [7]

#### 2.4. Instrumentation

Several types of instrumentation were used to record the events leading up to, during, and just after the impact. A full listing of each type of instrumentation and comments about each instruments performance can be found in Appendix A. Most instrumentation was mounted outside of the range tank for protection from debris. Clear polycarbonate ports and second surface mirrors were used to direct each instruments field of view towards the appropriate area of interest in the test chamber.

AEDC has extensive experience with digital X-ray systems, high speed video, and laser lit photography. All three of these systems were utilized during the test with the high speed video providing the most information about the impact event. Using high speed video to record the entire impact comes with several challenges. Pre-impact, the projectile and the hot hydrogen gas used to accelerate the projectile are barely visible in the dark range tank. Several flash bulbs are normally added to provide the necessary light to see the projectile in flight. During impact, a double-peaked, high-intensity impact flash occurs. This flash tends to saturate most digital photography sensors if not properly filtered. Post-impact, a hot, optically-dense plasma propagates through the test chamber, which tends to block the view camera equipment operating in the visual spectrum. Different values of neutral density (ND) filters were used for the DebrisSat program based on the AEDC staff's past experience with large energy impact testing. The basic impact camera settings for each different model are shown in the table below.

Table 2. Phantom Camera Settings

| Phantom Camera Model | v7.1                 | v7.1          | v711                  | v711                  | v711                  |
|----------------------|----------------------|---------------|-----------------------|-----------------------|-----------------------|
| DebrisLV             | <i>f</i> /16+ ND 3.0 | <i>f</i> /5.6 | <i>f</i> /11          | <i>f</i> /16 + ND 3.9 | <i>f</i> /22 + ND 0.9 |
| DebrisSat            | <i>f</i> /16+ ND 3.0 | <i>f</i> /5.6 | <i>f</i> /11 + ND 3.9 | <i>f</i> /22 + ND 3.9 | <i>f</i> /22 + ND 3.0 |

Two image sequences from the phantom camera are shown in figure 7 & 8 below. These images were selected at random points in the phantom camera movie as ideal representations of the quality of image that could be obtained with different light filters. Unfiltered views are often used to visually identify test article hit points while filtered cameras can see the plasma cloud expansion and partially record some of the failure mechanisms.

Figure 7 shows the DebrisSat test article being impacted and the subsequent expansion cloud. A 3.0 neutral density filter was used to reduce the light reaching the camera sensor so that the plasma cloud propagation could be adequately visualized. Thus even with six 110,000 lumen-second Meggaflash PF300 flash bulbs, the first frame of the video shows very little light reaching the camera sensor except for a small reflection on the outer layer of mylar. The next frames show the intense level of light generated from the impact. The formation of the luminous plasma ball is easily viewable behind the ND filter where it eventually produces enough light to illuminate the test chamber. Portions of the chamber remain visible until the cloud reaches the internal mirror mount and completely obscures the view field.

Figure 8 shows the results of the impact flash of the DebrisLV test with an unfiltered camera. The projectile and test article are clearly visible throughout the first few frames of the sequence. Light is generated from the surrounding flash bulbs which were triggered by the projectile velocity measurement instrumentation. Once the projectile impacts the test article, the plasma cloud produces enough light to begin saturating the camera sensor as evident by the pixilation of the 4<sup>th</sup> image in the sequence. The 5<sup>th</sup> image of the sequence shows where the plasma cloud saturates the entire camera sensor for a several frames in the video. In the final image the cloud has expanded and the light intensity is reduced.

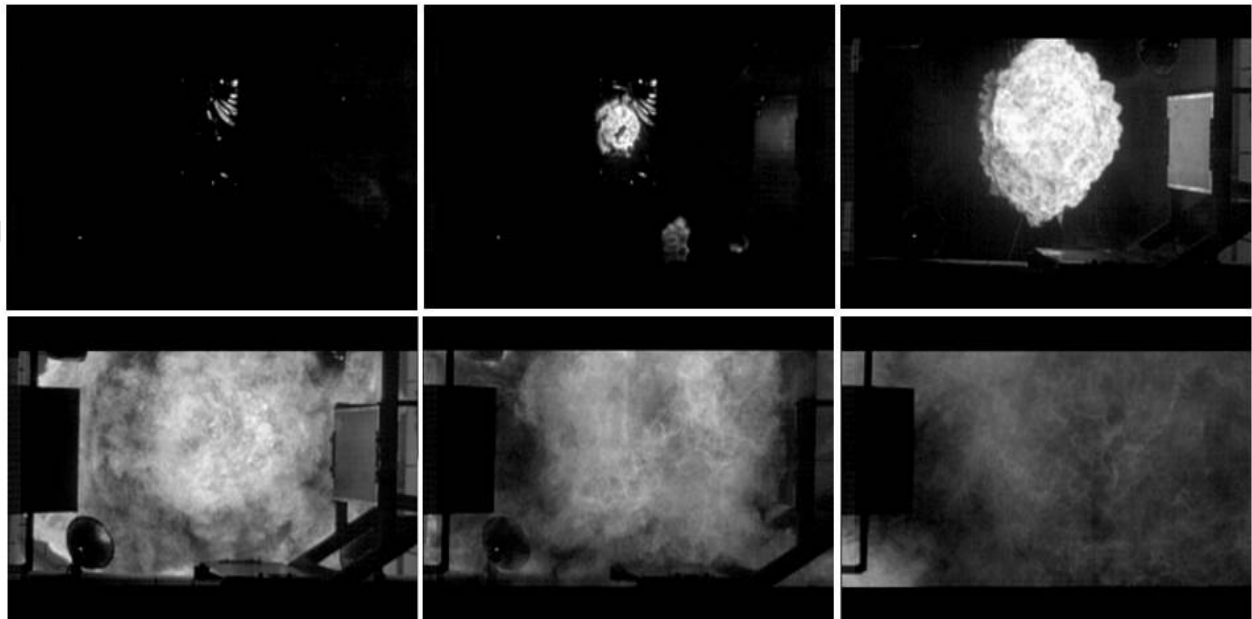
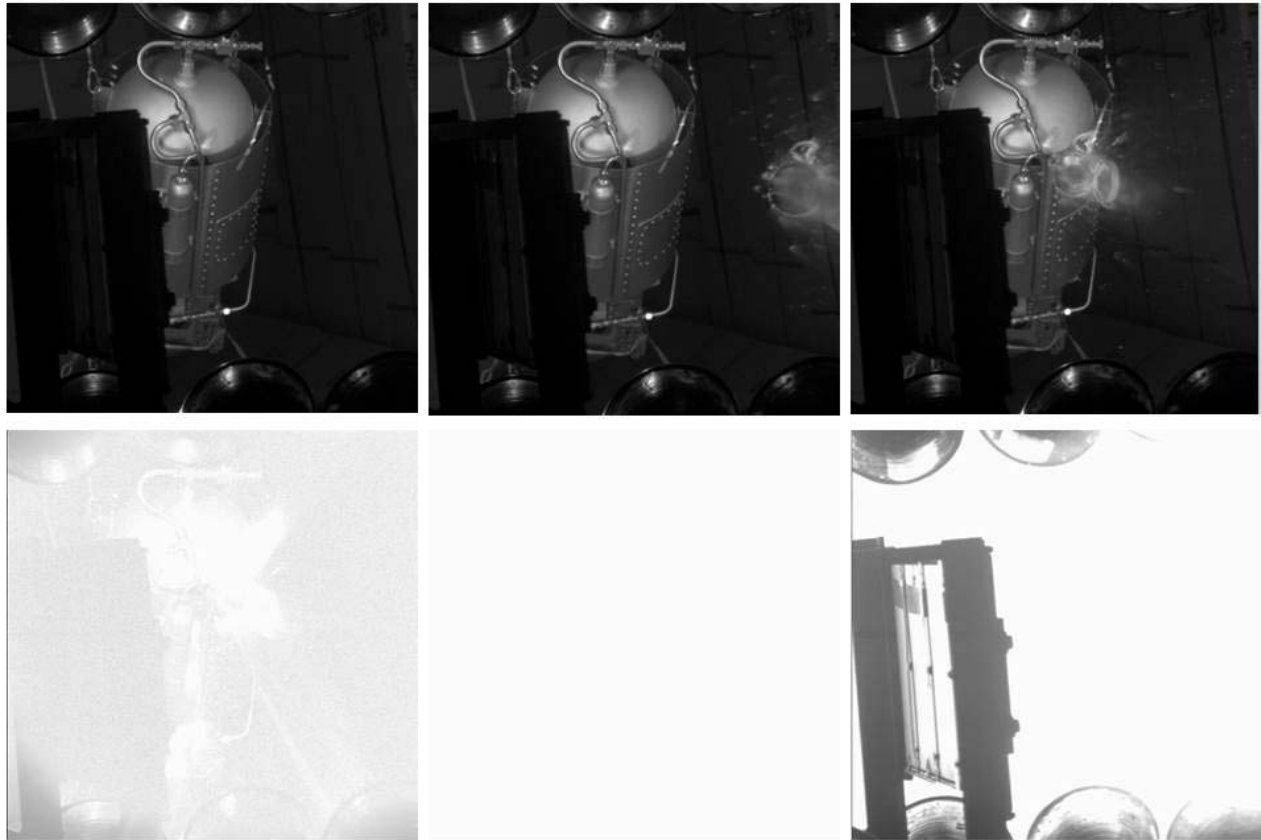




Fig. 7. Impact Flash Sequence (Phantom 7.1 –  $f/16$  – ND 3.0)

Fig. 8. DebrisLV Impact Flash Sequence (Phantom v711 –  $f/11$  - No Filter)



### 3. Data Interpretation and Recommendations for Future Test Programs

This test program provided a much needed update to empirical debris characterization data for hypervelocity satellite collisions. Currently large light gas guns are among the few ground test facilities that have the capability to accelerate masses greater than 100g to velocities that over 6km/s, the lower range of most on-orbit collisions in LEO. The operating envelop of these facilities is ever increasing as is most prominently evident by the comparison of the impact energy to target mass ratio for the DebrisSat and SOCIT programs. In the 1992 SOCIT test, performed before the Range G 84mm upgrade, the ratio was 78 J/g. The DebrisSat program performed in 2014 had over a 3X increase to 235 J/g due to the improved mass launching capability of the test facility.

The collection method developed by AEDC and NASA proved to be an effective way to collect the solid debris generated from the impact. The panels adequately collected the debris field with no damage evident to the facility containment tank. The posttest inspections revealed there were only a few locations where debris have reached the tank wall. The removal process was also a smooth operation. A working team of approximately 15 undergraduate/graduate students and research scientists were on hand to extricate the debris and soft catch panels. The complete removal and packing of the debris was accomplished in under a week. The only long lead time activities are X-ray mapping the debris distribution in the foam panels, fragment extraction, and the final fragment measurements and documentation. It is estimated there are 85,000 fragments larger than 2 mm in the collected DebrisSat debris. Sorting and documenting the fragments is expected to take up to three years.

In addition to all the recovered debris fragments, noteworthy data was obtained from a combination of AEDC, NASA, and Aerospace Corporation instrumentation. Interpreting data obtained from both instruments and physical samples is an ideal approach to better understand the failure mechanisms from a hypervelocity impact. This method also benefits advancements in hypervelocity impact computer simulations by allowing the instrumentation suite to provide information about the location of impact and then using the collected debris fragments to piece together the failure mechanism. Instrumentation and fragment data from the DebrisLV test was combined in this way to provide insight into the failure mechanism of complex structures.

Debris fragments and high speed video collected on the DebrisLV test article were supplied to The Aerospace Corporation for analysis. Their findings indicate that the vapor phase generated from the impact was a large contributor to much of the secondary damage on and around the test article. The use of multiple phantom camera views allowed the impact point to be easily identified. The direction of a gas jet formation from the impact could be clearly viewed using frame by frame analysis of the camera data. The jet impinged on a tank near the impact point that was strapped to the test article. The recovered pieces of this tank were found with significant damage. Since there was no evidence of cratering, which would indicate a solid material impact, the damage appears to have been caused solely by the gas phase jet. Additional debris fragments far away from the projectile impact point also showed heavy coatings of turbulently-applied vapor phase condensate. The deposited layers of metal vapor condensate do not weld to the underlying structures, but rather cool and contract. Since this process yields flakes that can be removed from the debris, the effect of the gas jet can be measured by the mass of the flakes.

The combination of intellectual and physical resources allowed the DebrisSat program to provide exceptional data to several aerospace organizations. This data will be used to improve models for satellite breakup, orbital debris environment definition, space situational awareness, shock shield designs, debris mitigation systems, hypervelocity impact simulations, and light gas gun operations. While the DebrisSat program will fill in several knowledge gaps about orbital debris and hypervelocity impacts, the test data will also lead to new areas of research. The overview of the test program configuration that is documented herein will hopefully provide a base line for future hypervelocity laboratory-based testing so that new research can be performed in a timely and efficient manner.

## Acknowledgements

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## Appendix A. Test Instrumentation

| Instrument   | Owning Organization       | Description   | Purpose/Comments   |
|--|---------------------------|---|--|
| 150 kV Flash X-ray                                 | AEDC                      | Dual-headed, orthogonally-mounted X-ray system.   | Determines exact projectile position for velocity calculations and ensures projectile integrity. Performed satisfactorily during test operations.  |
| 450 kV Flash X-Ray                                 | AEDC                      | Dual-headed, orthogonally-mounted X-ray system.   | Used to obtain two single frame images of impact debris formation. Some image quality issues.  |
| Phantom Digital Cine Cameras                       | AEDC/NASA                 | 3 Phantom v7.1 cameras;<br>3 Phantom v711 cameras;<br>2 Phantom v710 color cameras  | Recorded the condition of the projectile just prior to impact and at various stages of the impact event.   |
| Cooke Dicom Pro Laser Camera                       | AEDC                      | 2 cameras, illuminated with YAG laser   | Captured projectile snapshot at moment of impact.  |
| Acoustic/vibration sensors                         | NASA                      | Thin-film, self-adhesive, piezoelectric sensor pads attached directly to the test article.  | Time of arrival sensors - the sampling rate of these sensors was not fast enough to generate a waveform.   |
| AHMI Infrared Hypertemporal Imager                 | The Aerospace Corporation | 1K – 3K frames per second infrared imager; 128x160 max pixels with 1.2 – 0.5 millirad/pixel. InSb detector 3 $\mu$ m – 5 $\mu$ m band                                     | Captured infrared video of the post impact environment.  |
| AERHy Infrared Hyperspectral Imager (Spectrometer) | The Aerospace Corporation | 1K – 3K frames per second. Spectral range from 1.25 $\mu$ m to 4.0 $\mu$ m in one axis (600 spectral bins) x ~128 spatial bins; 1.0 - 0.5 milliradians per spatial pixel. | Documented chemical signatures in the infrared range.  |
| Portable Mass Spectrometer                         | The Aerospace Corporation |   | Collects data on the gases released from the impact and the late time reaction products.   |
| Witness Plate Assemblies                           | The Aerospace Corporation | Aluminum plate with embedded quartz, sapphire, and adhesive coupons   | Used to collect samples to investigate fragment darkening as a result of interaction with the impact gasses and plasma by collecting condensable species.  |
| Borescope Photron 1024 pci camera                  | The Aerospace Corporation | Capable of 10,000 fps   | Attempted to image the gas shock wave propagation through the DebrisLV target. This was not fielded on DebrisSat because of the target configuration. Did observe internal propagation of the high-speed plasma flash within the tank of the Pre-Shot Calibration Target |
| High-speed (ns) gated ICCD cameras                 | The Aerospace Corporation | ICCD camera adapted to a UV-visible spectrometer.<br>1 Controller per ICCD for trigger control.<br>SRS delay generator.   | Records spectrally and temporally resolved signatures of the plasma flash. 3-meter optical fiber was used to couple flash into spectrometer. 2 camera assemblies were used to cover spectral and/or temporal ranges.   |
| UV-Visible spectrometer                            | The Aerospace Corporation | UV-Vis spectrometer with integrating sphere for diffuse/spectral reflectance  | Attempted to gather chemical signature data in the visible range to help complete the chemical picture. Was not fast enough to match up well with the other spectral instruments.  |
| Agilent Exoscan Portable FTIR                      | NASA                      | Non-destructive infrared analysis of samples.   | Post test data gathering for debris darkening. It uses infrared light to create a chemical fingerprint of the compounds present on fragment surfaces. Was used to sample surfaces of Al tank and Debris Sat pre-and post test shots.                                     |

## Appendix B. Soft Catch Foam Configuration

