

AEDC-TR-15-S-2



DebriSat Hypervelocity Impact Test

**E. Marshall Polk
United States Air Force**

and

**Brian E. Roebuck
Aerospace Testing Alliance**

August 2015

Final Report for Period 1 – 15 April 2014

Statement A: Approved for public release; distribution unlimited.

**ARNOLD ENGINEERING DEVELOPMENT COMPLEX
ARNOLD AIR FORCE BASE, TENNESSEE
AIR FORCE TEST CENTER
UNITED STATES AIR FORCE**

NOTICES

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Technical Information Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

This report has been reviewed by the AEDC Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

APPROVAL STATEMENT

Prepared by:



E. MARSHALL POLK
United States Air Force



BRIAN E. ROEBUCK
Aerospace Testing Alliance

Reviewed by:



RICK RUSHING
Test Manager

Approved by:



HULAND C. SMITH
Technical Director
Space & Missiles Combined Test Force

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS					
1. REPORT DATE (DD-MM-YYYY) xx-08-2015		2. REPORT TYPE Final Report		3. DATES COVERED (From-To) 1 – 15 April 2014	
4. TITLE AND SUBTITLE DebrisSat Hypervelocity Impact Test				5a. CONTRACT NUMBER DASG60-00-C-0072	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Polk, E. Marshall United States Air Force and Roebuck, Brian E. Aerospace Testing Alliance				5d. PROJECT NUMBER 00013847	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Arnold Engineering Development Complex (AEDC)				8. PERFORMING ORGANIZATION REPORT NO. AEDC-TR-15-S-2	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NASA Orbital Debris Program Office Attn: Dr. J.C. Liou 2101 NASA Parkway Houston, TX 77058				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Statement A: Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES Available in the Defense Technical Information Center (DTIC).					
14. 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/sec. A nonfunctional, full-scale representation of a modern satellite called the DebrisSat was destroyed in the enclosed range environment. Several modifications to the range facility were made to ensure quality data were obtained from the impact events. The facility modifications were intended to provide a high-impact energy-to-target-mass ratio (>200 J/g), a nondamaging method of debris collection, and an instrumentation suite capable of providing information on the physics of the entire impact event.					
15. Subject Terms 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					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19A. NAME OF RESPONSIBLE PERSON Marshall Polk
A. REPORT Unclassified	B. ABSTRACT Unclassified	C. THIS PAGE Unclassified			19B. TELEPHONE NUMBER (Include area code) (931) 454-5965

This page is intentionally left blank.

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Complex (AEDC), Air Force Test Center (AFTC), at the request of the Dr. J. C. Liou for the NASA Johnson Space Center (JSC), Houston, TX. Testing was conducted in Range G of the Space and Missiles Combined Test Force (CTF) from 1 to 15 April 2014 under AEDC Project Number 13847.

This page is intentionally left blank.

CONTENTS

	<u>Page</u>
1.0 INTRODUCTION.....	3
1.1 General.....	3
1.2 Previous Orbital Debris Testing at AEDC.....	3
2.0 METHODS, ASSUMPTIONS, AND PROCEDURES	4
2.1 Test Objectives	4
2.2 Test Facility.....	5
2.3 System Under Test	5
2.3.1 5x Scale Multishock Shield	6
2.3.2 DebrisLV	7
2.3.4 DebrisSat	8
2.4 Test Planning.....	10
2.4.1 Launcher Configuration	10
2.4.3 Projectile Design	11
2.4.4 Target and Soft Catch Installation	12
2.4.5 Hazard Mitigation	14
3.0 RESULTS AND DISCUSSION	14
3.1 Launcher.....	14
3.2 Projectile.....	14
3.3 Debris Collection System.....	15
3.4 Instrumentation	16
5.0 SUMMARY	19
REFERENCES.....	20

FIGURES

Figure

1. SOCIT Installed in Range G Tank with Foam Paneling.....	4
2. Shock Shield Installed in Range G Tank.....	6
3. DebrisLV Assembly	7
4. DebrisSat Top View (Looking from Zenith to Nadir).....	9
5. DebrisSat Component Layout.....	9
6. Projectile Acceleration Profile	10
7. DebrisSat Projectile Assembly.....	11

8. Soft Catch Partial Construction.....	12
9. Front Soft Catch Opening	13
10. X-Ray of DebrisSat Projectile Base Separation	15
11. Posttest Softcatch.....	16
12. DebrisSat Impact Flash Sequence (Phantom 7.1 – f /16 – ND 3.0)	17
13. DebrisLV Impact Flash Sequence (Phantom v711 – f/11 - Unfiltered)	18

TABLES

Table

1. DebrisSat Component Characteristics.....	8
2. Measured Projectile Velocity and Mass	14
3. Phantom Camera Settings.....	17

APPENDICES

Appendix

A. Test Instrumentation	21
B. Soft Catch Foam Configuration	23

1.0 INTRODUCTION

1.1 GENERAL

The goal of the NASA DebrisSat Program is to update space breakup models using data from fragments generated by a hypervelocity collision involving a modern satellite in low Earth orbit (LEO). The breakup models currently used by DoD and NASA before the DebrisSat Program were partially based on the 1992 Satellite Orbital Debris Characterization Impact Test (SOCIT) project in the AEDC Range G facility (Ref. 1). This previous test project impacted targets that were representative of 1960s-era satellite technology. Collisions involving modern satellites such as Iridium 33 and Fengyun-1C indicated discrepancies between model predictions and the observed data. The DebrisSat Program was thus created to resolve these discrepancies. The main component of the test project was the DebrisSat system under test (SUT), an engineered model of a modern, 60-cm/50-kg class LEO satellite. Through a high-energy hypervelocity impact, the satellite would be catastrophically fragmented with all substantial particles being collected for further analysis. Characterization of the breakup fragments down to 2 mm in size would later be performed from the collected debris. The obtained data would include fragment size, area-to-mass ratio, density, shape, material composition, optical properties, and radar cross-section distributions. These data would then be used to supplement the satellite breakup models to better describe the fragmentation outcome of a modern satellite.

1.2 PREVIOUS ORBITAL DEBRIS TESTING AT AEDC

The SOCIT project provided key data to the DoD and NASA satellite breakup models for on-orbit collisions. During this project AEDC performed high-energy impact tests using a solar panel, an inter-stage adapter, and a complete surplus flight-ready Navy transit navigation satellite. All of the hardware was surplus material that had been fabricated in the 1960s. The satellite itself was 46 cm diameter by 30 cm high and weighed 34.5 kg. The 63.5-mm-diam launcher in Range G was used to fire a 150 g solid aluminum sphere into the satellite at 6.1 km/sec providing 78 J/g impact energy-to-target-mass ratio (Ref. 2).

The SOCIT project was mutually beneficial to DoD, NASA, and AEDC. DoD and NASA obtained data for their breakup model, and AEDC acquired important information about debris collection materials and how they could be used in future testing. These debris collection systems are often referred to as “soft catch” due to their ability to capture debris particles with minimal changes to the initial impacting shape. SOCIT chose to use polyurethane foam with densities of 60 kg/m³, 96 kg/m³, and 192 kg/m³. Boards of the foam were cut and attached to rigid plywood backing that was then affixed to the inside of the range tank. The foam was configured in multiple layers so that the first layers were low density, either 60 kg/m³ or 96 kg/m³, and the final layers were constructed of the 192 kg/m³ foam. This dual-density design reduced overall penetration depth and reduced debris deformation. Slow debris was captured in the initial layers of low-density foam, and debris traveling at high velocity was captured in the layers of dense foam (Ref. 3).

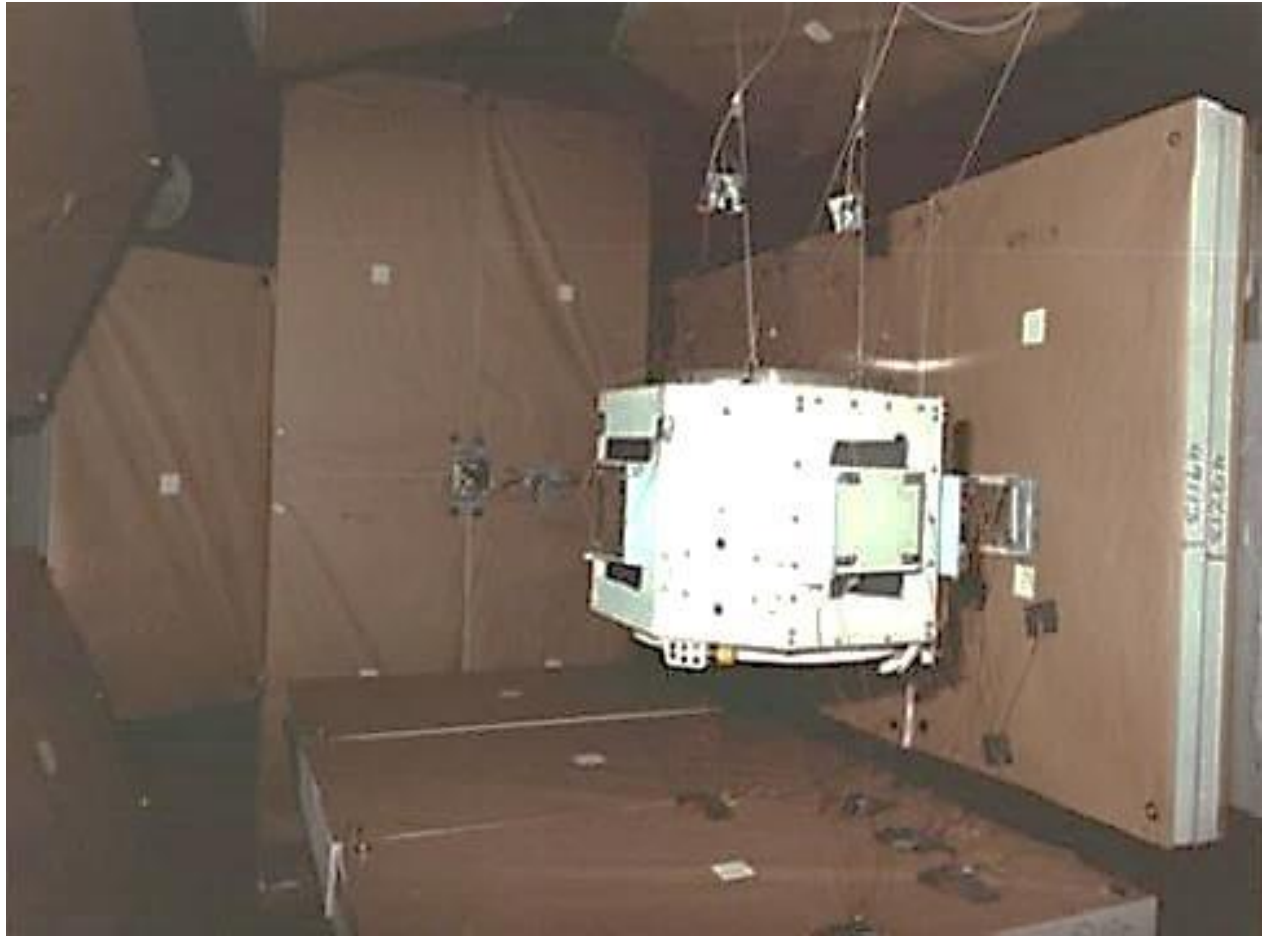


Figure 1. SOCIT Installed in Range G Tank with Foam Paneling

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

2.0 METHODS, ASSUMPTIONS, AND PROCEDURES

2.1 TEST OBJECTIVES

The main objectives presented to AEDC at the beginning of the NASA DebrisSat Program was to provide the maximum possible impact energy into the SUT 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 and AEDC experience with debris collection systems. General requirements were as follows:

- Targets: Scaled Multishock Shield, DebrisLV, and DebrisSat
- 500-600 g hollow aluminum and nylon projectile
- 7 km/sec (± 0.1 km/sec) projectile velocity
- Test chamber pressure less than 267 Pa (2 torr)
- Soft catch system based on low-density foam material to collect resulting impact debris
- Record target impact data through AEDC facility high-speed instrumentation

2.2 TEST FACILITY

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/sec. The facility routinely launches projectiles at velocities between 3-6 km/sec. Projectiles up to 203 mm (8.0 in.) diameter are launched into a 3-m (10-ft)-diameter, 283.5-m (930-ft)-long instrumented tank that can be maintained at pressures from 0.2 torr to 1.7 atmospheres. The launcher started test operations in 1962 as a 63.5-mm (2.5-in.) bore diameter but has been significantly upgraded over the years to launch larger masses at high velocities with lower peak acceleration loads. Currently the facility has three sizes of interchangeable barrels: 84 mm (3.3 in.), 102 mm (4 in.), and 203 mm (8 in.).

Range G is a unique light gas launcher not only because of its size, but also because of its ability to minimize acceleration loads (g's). In 1994 the launcher was upgraded to the current barrel and pump tube configuration. This upgrade increased the light gas pumping capability and reduced peak acceleration loads by using a larger diameter pump tube and lengthening the barrel. This launch upgrade gave AEDC the capability to accelerate projectiles with complex geometries that would have often failed in the earlier 63.5-mm launcher configuration.

2.3 SYSTEM UNDER TEST

The test team chose to perform three impact experiments of which two utilized the soft catch debris collection system. The first test was a checkout shot funded by AEDC to verify that the 7.0 km/sec (± 0.1 km/sec) impact velocity could be attained with the Range G launcher. This test utilized a NASA-supplied 5x scaled version of a multishock shield constructed by the Hypervelocity Impact Technology (HVIT) Group at NASA Johnson Space Center. No soft catch was used on the validation shot. The second test was a full facility checkout shot using a low-cost target called DebrisLV. This SUT was a 15-kg 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 multilayer insulation. DebrisSat's internal components were structurally similar to real flight hardware but were nonfunctional.

2.3.1 5x Scale Multishock Shield

The first target, a 5x scale multishock shield from NASA, was a piggyback target added to the checkout shot to obtain additional hypervelocity impact data. The test article was a 5x scaled-up version of a multi-shock shield (Fig. 2) which consisted of five separate bumpers. Four bumpers were fiberglass construction and one was steel mesh. Two sheets of Kevlar fabric were placed after each bumper. The overall length of the test article was 2.65 m. NASA tested a similar configuration using only the four fiberglass bumpers for an inflatable module project several years prior to the Debrisat Program. The previous test used a 1.4-cm-diam spherical aluminum projectile fired from a smaller light gas gun. To handle the larger Debrisat projectile, NASA ran ANSYS AUTODYN Hydrocode simulations of the impact event to determine what strengthening was required. This analysis indicated that the additional layer of steel mesh would be required to fragment the cylindrical projectile design (Ref. 4). The recovered posttest assembly revealed that the NASA analysis was correct. The projectile fragmented early in the impact sequence, and the final bumper had no penetrations.



Figure 2. Shock Shield Installed in Range G Tank

2.3.2 DebrisLV

The second target, shown in Fig. 3, was a 17.6-kg structure intended to emulate common upper stage construction in LEO. The intent of this impact test was to obtain data to better understand failure modes during hypervelocity impact fragmentation. The assembly consisted of a deep-drawn, welded 5154 aluminum tank with a 3.2-mm wall thickness. Realistic material dimensions and attachment methods (rivets, adhesive bonding) were used on DebrisLV where the six longerons (aluminum, stainless steel, copper) were bonded to the tank and also where a 6061 aluminum skin was riveted to the longerons. Two 6061 aluminum strap-on tanks were then added to the aluminum skin. An additional flight-qualified, thin-walled titanium tank and roll-control thruster (RCT) assembly was attached to the base of the aluminum tank. Four access ports were distributed at 90 deg around the perimeter of the tank, with three of the four ports covered with riveted access plates.

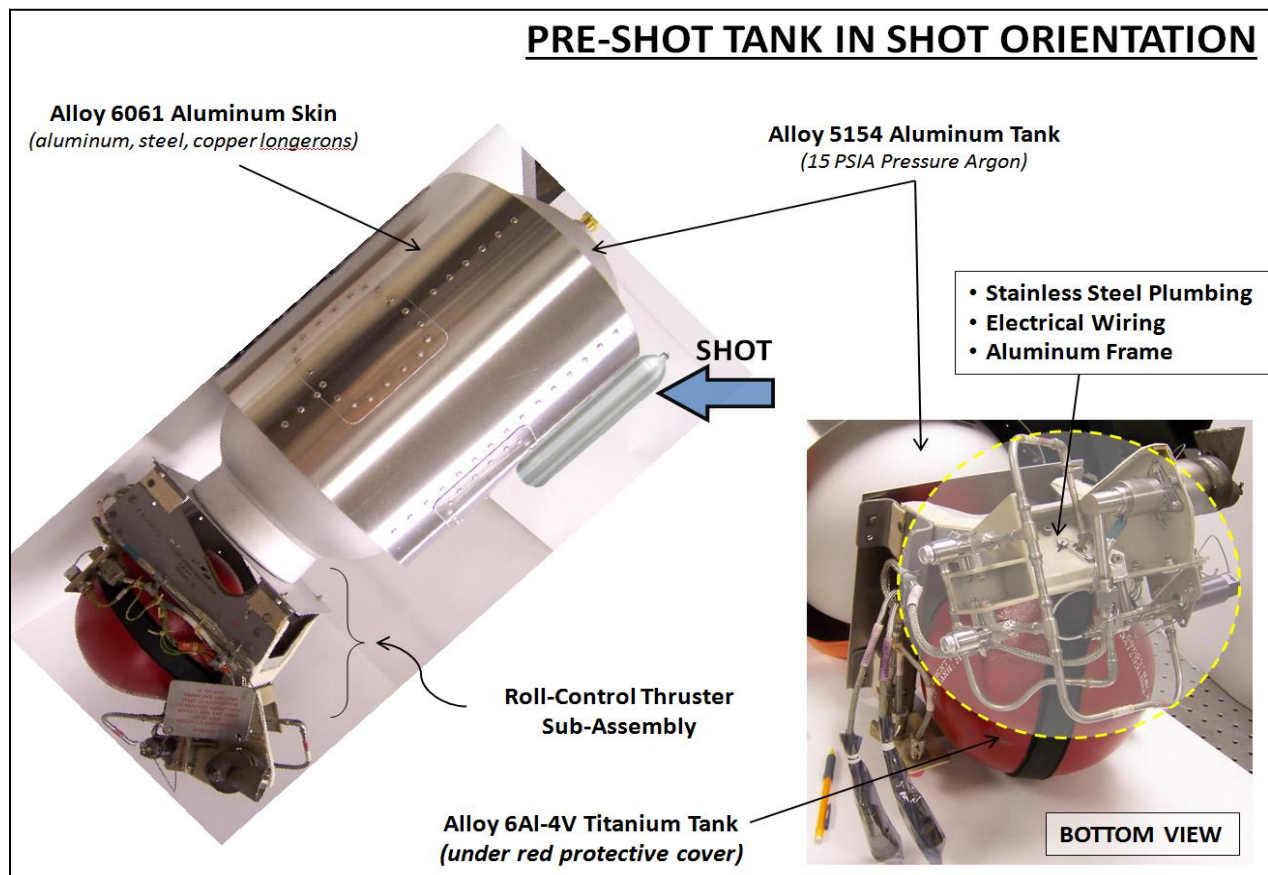


Figure 3. DebrisLV Assembly

The DebrisLV was fastened to mounts on the range tank ceiling and floor with six screw-links and lengths of steel-braided cable. The SUT was hung at approximately 45 deg inclination in relation to the gun line. The DebrisLV tank and the RCT subassembly were both pressurized in order to simulate residual propellants contained in on-orbit vehicles. The titanium RCT contained 6.3L helium gas at 50 psia, and the tank contained 44L xenon gas at 30 psia.

2.3.4 DebrisSat

The DebrisSat satellite was engineered to emulate the components, subsystems, materials, and construction techniques of a modern LEO satellite. DebrisSat is a hexagonal body containing seven compartmentalized bays. The nadir and zenith panels along with the vertical struts connecting them are constructed from anodized AL 6061-T6. Panels A-F and the structural ribs between the bays are constructed of composite sandwich structures with an AL 5052 honeycomb core and M55J carbon fiber face sheets. The basic system characteristics of the DebrisSat are given in Table 1. A detailed overview of the DebrisSat structural layout is shown in Figs. 4 and 5.

Table 1. DebrisSat Component Characteristics

Item	Description
Spacecraft Mass	50 kg
Main Body Size	60 cm (Dia) × 50 cm (H)
Physical Envelope	84 cm (L) × 61 cm (W) × 68 cm (H) (including extended components)
Deployables	Yes; one solar panel deployed
Propulsion	Yes; AL COPV tank pressurized to 267 Pa (2 torr) with nitrogen to emulate end-of-life
Thermal Control	Yes; all plumbing but no working fluid
Battery	Yes; inert lithium-ion battery packs (i.e., no electrolyte)
Avionics	Yes; all hardware (harnesses and processing boards), but no software
Materials	AL 6061-T6, AL 5052, AL 3003, aluminum purity: <99.9% , SS (316, 304), copper, germanium, glass (solar cells), NBK7 glass, titanium, sapphire, T1000 fiber, M55J carbon fiber, PVE film (sheet, wire), kevlar, HDPE, polyurethane plastic, mylar sheets, polyimide film, kapton tape, and epoxies (CV10-2568, CV2960, CV2289, EC2216)

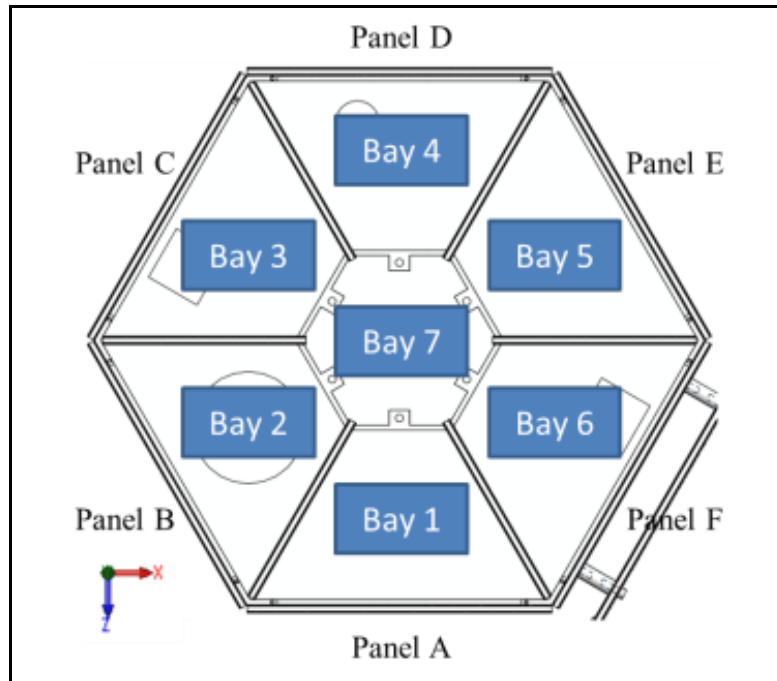


Figure 4. DebrisSat Top View (Looking from Zenith to Nadir)

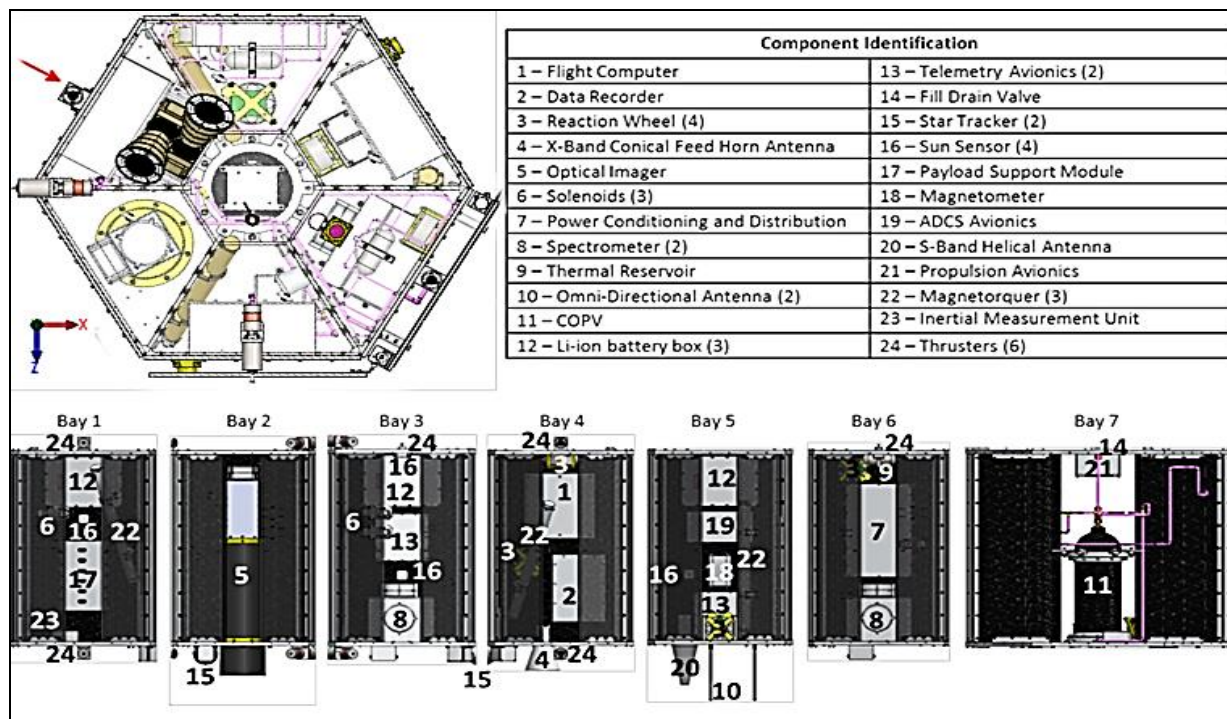


Figure 5. DebrisSat Component Layout

DebrisSat was also designed with safety considerations in mind since several personnel would be exposed to the debris fragments. The satellite contained no beryllium parts and utilized inert lithium-ion batteries (no electrolyte) to minimize exposure to hazardous materials during posttest handling.

DebrisSat used stainless-steel eye bolts on the circumference of the zenith and nadir panels which were then hooked into braided stainless-steel cables for hanging in the test tank. Screw-links attached the cables to mounts on the floor and ceiling of the tank as well as to the eye bolt mount points on the DebrisSat itself.

2.4 TEST PLANNING

Based on the test requirements, the test project required a substantial planning effort to provide a good method for conducting the three test entries in the Range G test facility. Multiple public and private organizations involved in the effort made regular communications via phone conferences and site visits. This approach ultimately allowed the team to create detailed plans and methods resulting in a maximization of data obtained with minimal risk. Due to the unique nature of this test, the AEDC range personnel experience was key to guiding program personnel through the process of test design. The overall planning and support role of AEDC helped blend the expertise of each group into a single team that was able to meet several different objectives.

2.4.1 Launcher Configuration

The Range G launcher was configured with 39.6 m of 84-mm-diam launch tube to reach the 7 km/sec velocity requirement. This velocity is the upper limit of the Range G operating curve and required minimization of the projectile mass and a careful selection of the gun configuration. Prior to the DebrisSat Program, AEDC had launched projectiles weighing 450 gm at 6.94 km/sec. 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 gm. A very high acceleration load was imposed on the projectile to reach the 7 km/sec target velocity. Peak instantaneous acceleration was just under 87,000 g's, which is 20,000-50,000 g's greater than the typical AEDC 3-6 km/sec launch cycle.

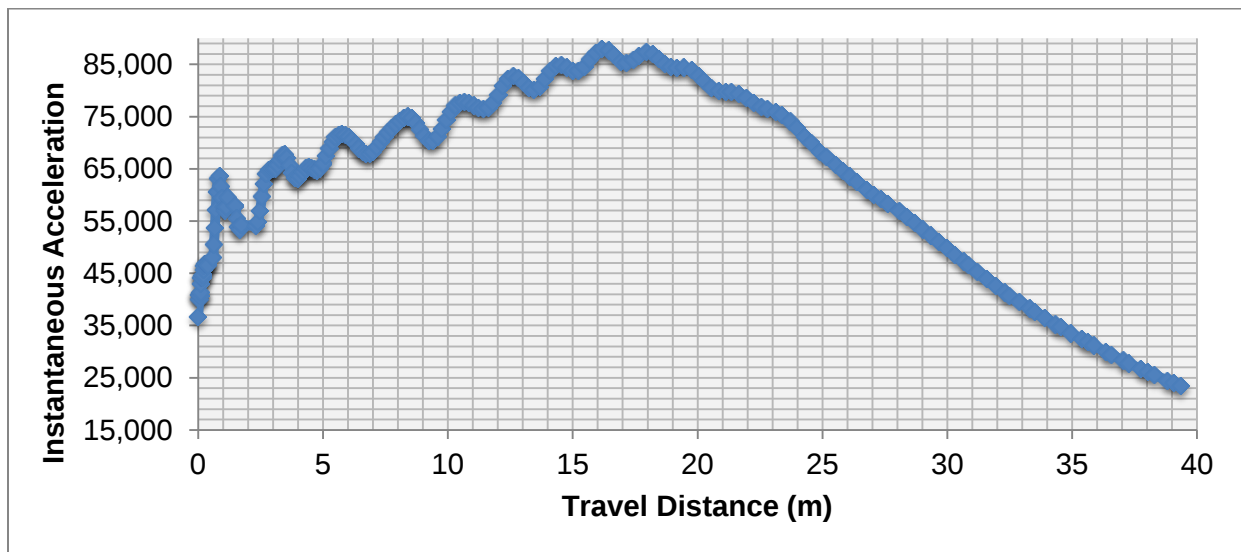


Figure 6. Projectile Acceleration Profile

2.4.3 Projectile Design

The projectile was based on a successful design from a previous AEDC hypervelocity impact project. The design (Fig. 7) used a hollow aluminum cylinder made of 7075-T651 aluminum with a nylon sleeve. During assembly the aluminum cylinder is coated with a light layer of room temperature vulcanization (RTV) silicone to prevent gas intrusion and then threaded into the nylon sleeve. The nylon sleeve provides a soft interface to the launcher bore and maintains a seal to prevent gun gas leakage around the projectile. An aluminum cap is threaded into the front of the sleeve to provide a flat face for impact. Unlike the sphere and sabot projectile design as used in the SOCIT test series, this configuration allows the entire launch package mass and resultant kinetic energy to be transferred into the target.

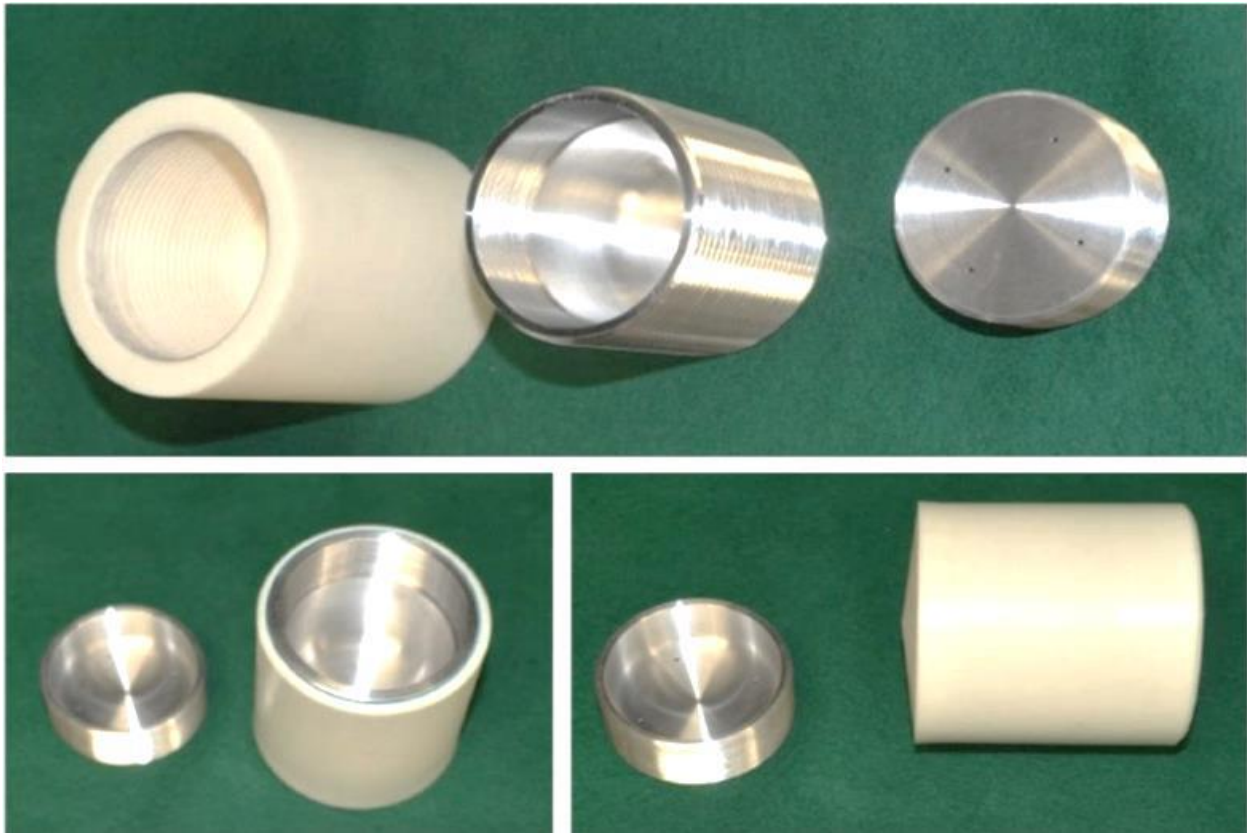


Figure 7. DebrisSat Projectile Assembly

The previous design of this projectile was a 1,000-g version that was successfully launched at velocities ranging from 4 to 6 km/sec. 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 strength in order to reach the 400- to 500-gm 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. The computer simulation results indicated 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 in free flight.

2.4.4 Target and Soft Catch Installation

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. The foam design was a more costly option, but it was selected for the DebrisSat project since fidelity of the captured 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 (Fig. 8) that was developed for the 10-ft inside diameter AEDC range tank. This geometry allows more spacing between the impact point and the front face of the foam panels, reduces foam damage from the impact blast wave, allows the debris cloud to expand slightly further, and reduces the mass that impacts a single piece of foam. The octagon shape was configured to provide a nearly equidistant path from the test article to provide a better characterization of the debris field.

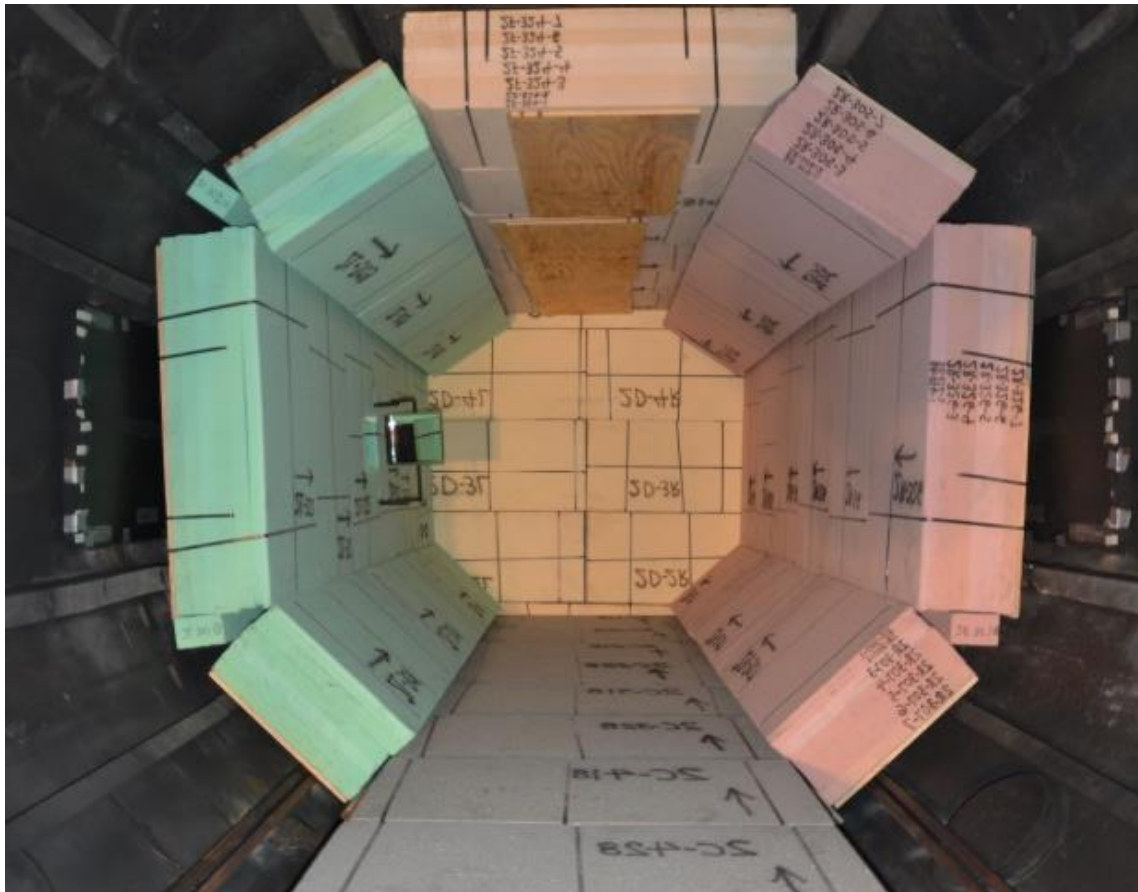


Figure 8. Soft Catch Partial Construction

The second change was a modification to the foam density gradient. The DebrisSat foam soft catch panel design used an improved density gradient by adding more low-density outer layers and using three differing foam densities per panel instead of just two. 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. The three-layer approach added the capability to capture high-speed debris while still retaining the benefits of the low-density outer layer. The three densities of foam were 48 kg/m^3 , 96 kg/m^3 , and 193 kg/m^3 . The foam was Last-A-Foam FR-3700 Performance Core Series from General Plastics. The foam boards were all pre-cut to 2 x 4 ft., carefully stacked in the density gradient, and bound to plywood backing using nylon banding straps. Simple strapping was favored over adhesives because it would be very easy to separate the layers for analysis after the test. After strapping, each panel's front, rear, and individual 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 foam was also color coded to assist in determining the location of various loose foam pieces found posttest. Details on the layer configuration for each type of panel can be found in Appendix B.

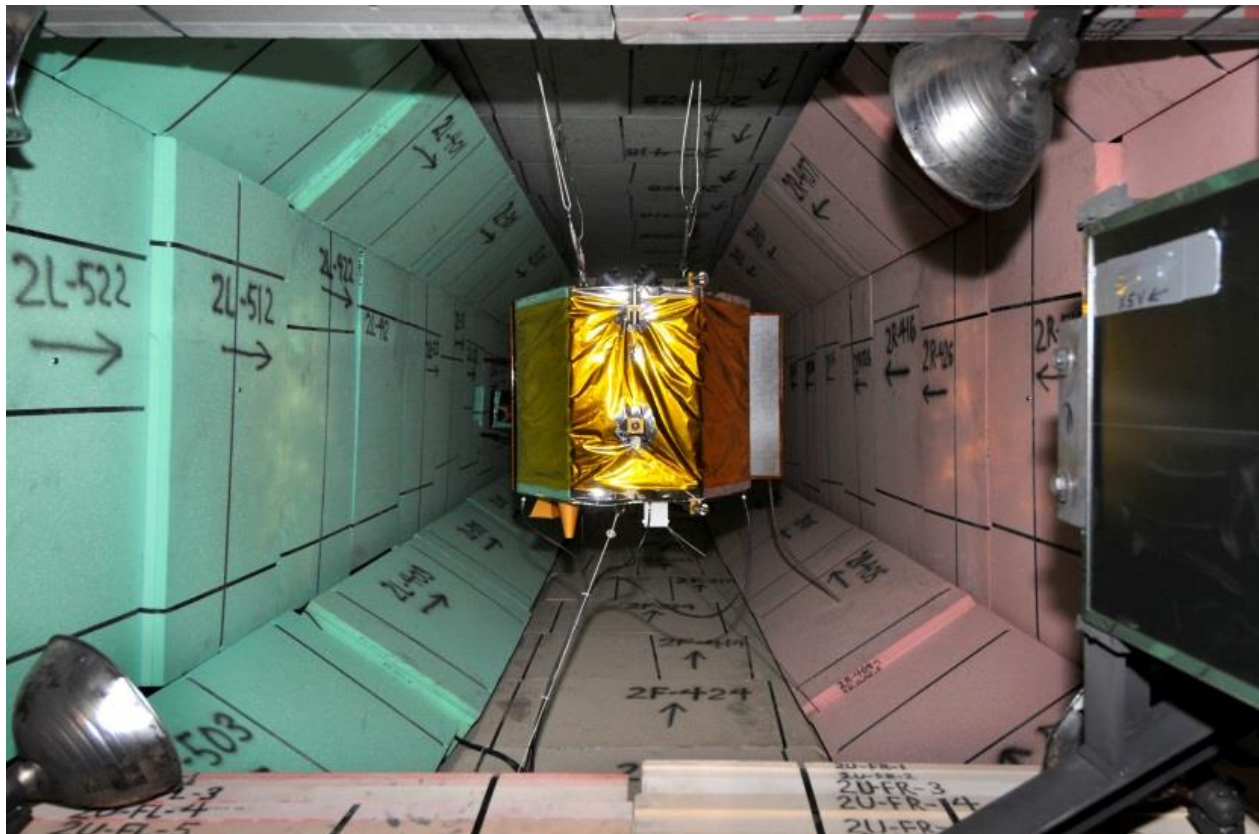


Figure 9. Front Soft Catch Opening

2.4.5 Hazard Mitigation

A project plan was developed that avoided the use of toxic materials in the targets, the soft catch materials, and the projectile. Such materials make the collection of postshot debris extremely difficult and costly. One such material was the lithium ion batteries that were to be placed in the DebrisSat target. The electrolyte material would have created toxic conditions after impact in the target tank. The issue was avoided by designing and fabricating nontoxic versions of the batteries.

Another concern was the foam material used in the soft catch panels. The foam was selected not to have dangerous chemicals or materials in the ingredients, but it did create many fine particles when crushed. Personnel in the target tank after a shot could be exposed to airborne dust contamination from pulverized foam panel material. A plan to use personal protective equipment (PPE) to mitigate this hazard was put into place for all personnel entering the tank after a shot. All groups involved in the test worked together to determine what PPE was required, what training was required, and who provided the PPE for the test. NASA provided forced-air-filtered helmet style units that were easy to use and very effective for all of the personnel participating in the Debris assessment and clean-up. AEDC provided the PPE training and also a plan for how to safely remove the debris and collect it for later analysis.

3.0 RESULTS AND DISCUSSION

3.1 LAUNCHER

The measured muzzle velocity on all three tests was less than the 7.0 km/sec value predicted by the AEDC gun code. The velocity values as measured by the continuous-wave x-ray detection system are shown in Table 2.

Table 2. Measured Projectile Velocity and Mass

Test	Velocity (km/sec)	Mass (gm)
Checkout	6.91	598
DebrisLV	6.91	598
DebrisSat	6.79	570

Inspection tools such as video borescopes, laser bore scanners, and physical bore measurement gages were used to quantify the launcher condition 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 project with a 7.0 km/sec muzzle velocity objective. The DebrisSat Program only had three data points, but the data indicate that the launcher configuration could be used to perform more shots without concern for accelerated facility wear.

3.2 PROJECTILE

During each test the projectile was able to successfully impart the total muzzle energy into each target. Unfortunately the lightweight design created a mechanical failure in the aft part of the assembly that was recorded on x-ray images taken during free flight (Fig. 10). Increasing the outside diameter of the aluminum reduced the cross-sectional surface area of the nylon sleeve that connected the solid flat base of the portion of the body that contained the threads. This

area reduction weakened the model structure and contributed to the failure. However, the area reduction alone was not enough to cause a failure. The Range G launcher has a taper of the bore diameter that effectively reduces the diameter toward 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 the large taper in the barrel assembly also contributed to the projectile failure during launch. Additional finite-element simulations were performed after the test project using as-measured projectile and launcher geometry. These simulations showed that the gun taper increased stress in the nylon when there was minimal erosion. These types of failures are extremely rare in the standard operating velocity of Range G as the wear and launcher taper are properly matched. This single project failure mode indicates that further evaluation of 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 both the DebrisLV and DebrisSat impact tests were successfully met.

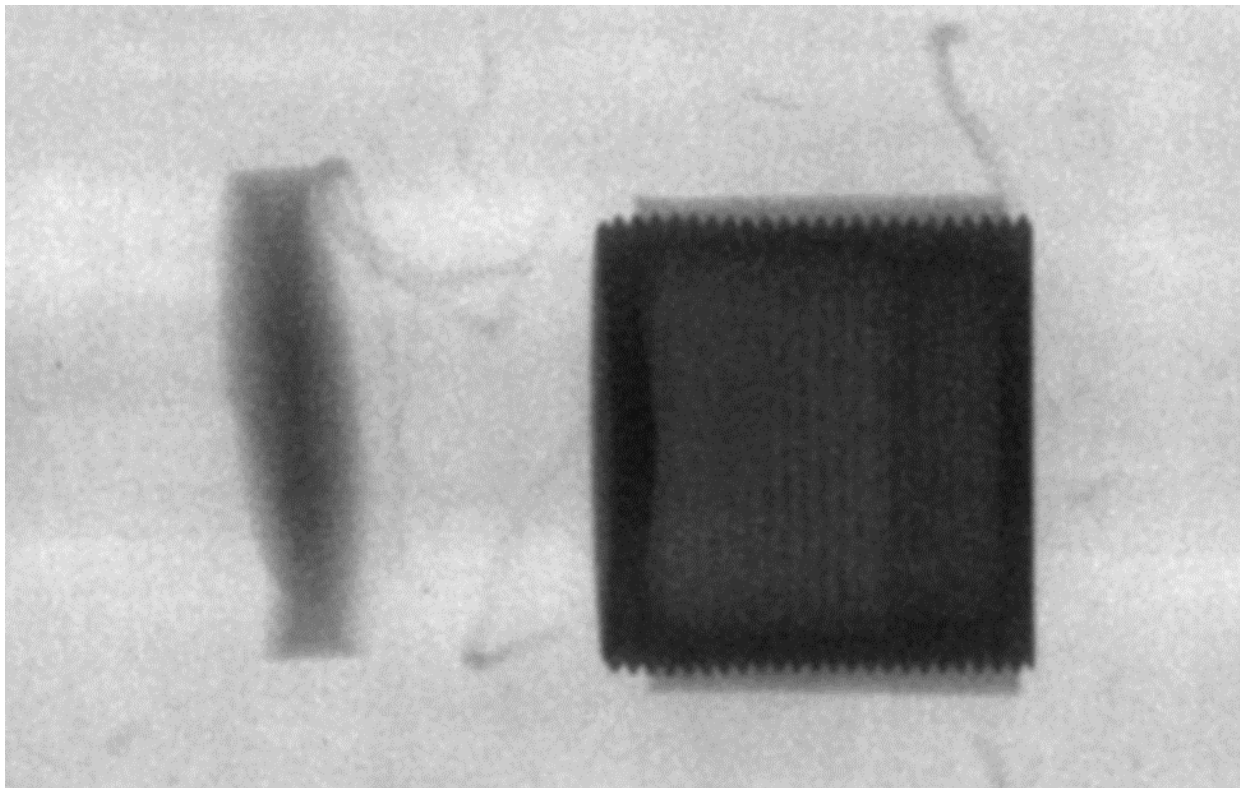


Figure 10. X-Ray of DebrisSat Projectile Base Separation

3.3 DEBRIS COLLECTION SYSTEM

The posttest inspections revealed there were only a few locations where debris may have reached the tank wall. The top foam panel and plywood backing just above the test article was severely fragmented on each shot (Fig 11) and may have allowed debris to impact the tank wall. Several of the foam panels that comprised the rear wall of the debris collection system were knocked down by the impact blast during each test. The rear wall was braced between the DebrisLV and Debrisat test, which lessened the number of panels that fell down. Very little debris made it past the rear wall even with the impact blast knocking down the panel.

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 2 days following each shot. The only long-duration items were X-ray mapping of the debris distribution in the foam panels, fragment extraction, and the final fragment measurement and documentation. It is estimated that there were approximately 85,000 fragments larger than 2 mm in the collected Debrisat debris. Sorting and documenting the fragments is expected to take NASA and the University of Florida up to 3 years.



Figure 11. Posttest Softcatch

3.4 INSTRUMENTATION

AEDC's digital X-ray systems, high-speed video, and laser-lit photography systems were utilized during the test. NASA and the Aerospace Corporation also brought specific instrumentation for this test. A full listing of each type of instrumentation and comments about the instrument's 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 instrument's field of view toward the appropriate area of interest through the projectile entrance opening in the front of the soft catch (Fig 9).

Using high-speed video cameras for the large energy impact on the Debrisat project presented several challenges. Before 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 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. After impact, there exists high-temperature optically dense plasma propagating through the test chamber which tends to block the view of camera equipment operating in the visual spectrum. To account for high levels of impact flash, different values of neutral density (ND) filters were used for the DebrisSat project that were chosen based on AEDC experience with large-energy impact testing. The basic impact camera settings for each different model are shown in Table 3.

Table 3. Phantom Camera Settings

Phantom Camera	v7.1	v7.1	v711	v711	v711
DebrisLV	f/16+ ND 3.0	f/5.6	f/11	f/16 + ND 3.9	f/22 + ND 0.9
DebrisSat	f/16+ ND 3.0	f/5.6	f/11 + ND 3.9	f/22 + ND 3.9	f/22 + ND 3.0

Two image sequences from the phantom cameras are shown in Figs. 12 and 13. These images were selected at various points in the video to show representations of the quality of image that were 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.

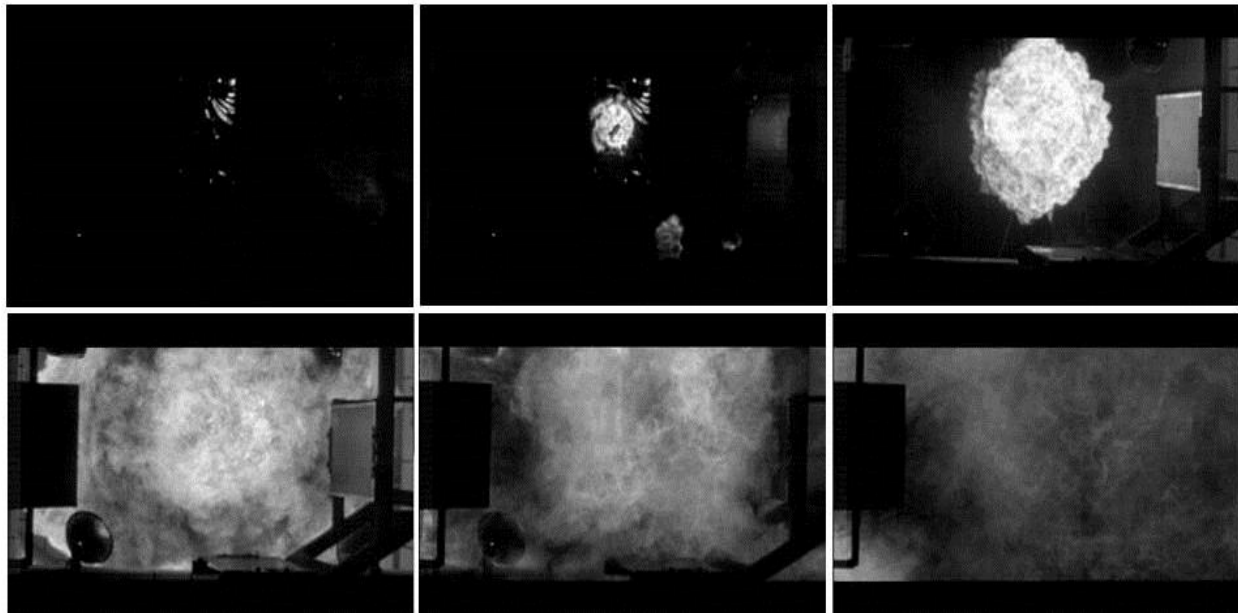


Fig. 12. DebrisSat Impact Flash Sequence (Phantom 7.1 – f /16 – ND 3.0)

Figure 12 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-sec 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 impact plasma cloud reaches the internal mirror mount and completely obscures the view field.

Figure 13 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 4th image in the sequence. The 5th image of the sequence shows where the plasma cloud saturates the entire camera sensor for several frames in the video. In the final image the cloud has expanded and the light intensity is reduced.

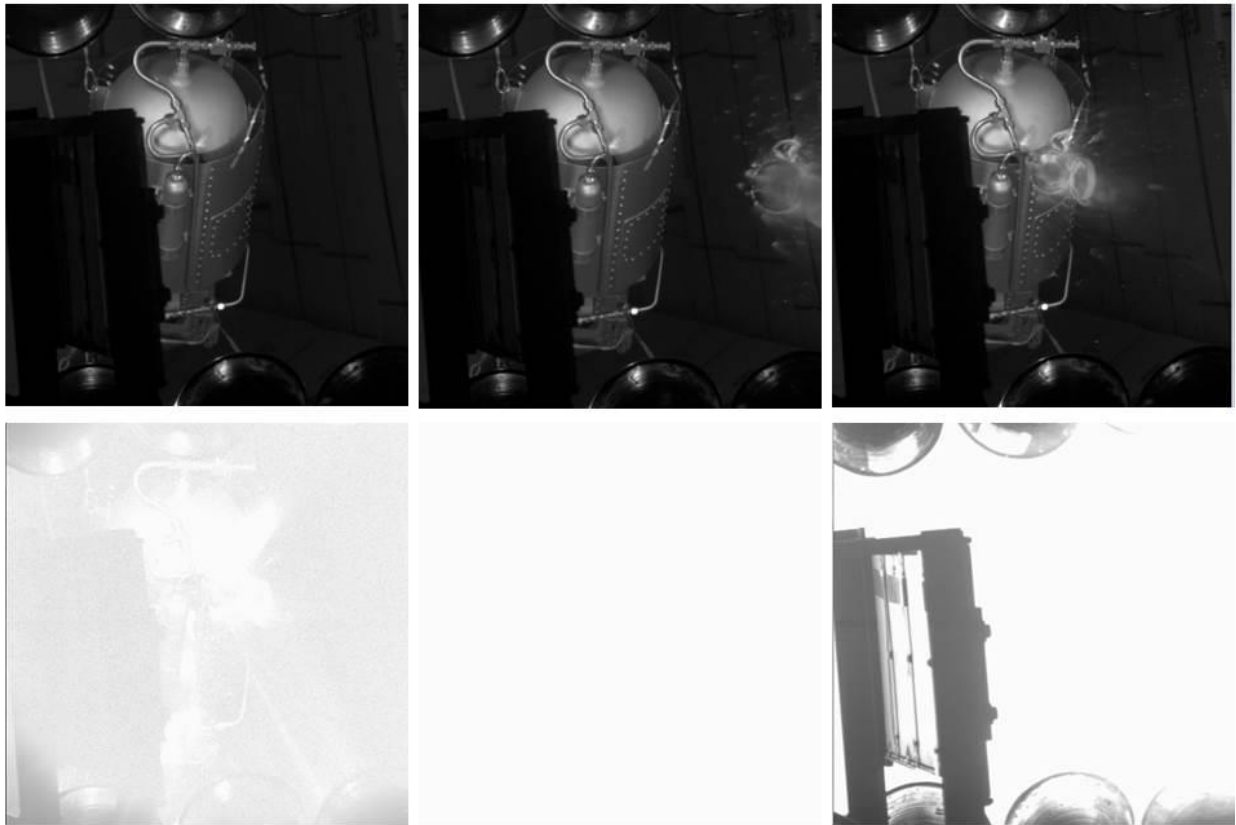


Fig. 13. DebrisLV Impact Flash Sequence (Phantom v711 – f/11 - Unfiltered)

Analysis of the instrumentation by The Aerospace Corporation indicates that the vapor phase generated from the impact was a large contributor to much of the secondary damage on and around the test article. Hypervelocity jetting is a known phenomenon that occurs during high-speed impacts (Ref. 5), but the effects of the jet on surrounding structures has not been studied. The use of multiple phantom camera views looking at the front of DebrisSat 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 cool and contract. Since this process yields flakes that can be removed from the debris, the effect of the gas jet was measured by the mass of the flakes (Ref. 6).

4.0 CONCLUSIONS

The Debrisat impact provided NASA with sufficient information to update their empirical debris characterization models for hypervelocity satellite collisions. The collection method developed by AEDC and NASA proved to be an effective way to collect the solid debris generated from hypervelocity impacts. The launcher did not reach the 7 km/sec desired velocity, but the actual velocity on each test was sufficient for the test project objective. The panels adequately collected the debris field with no damage evident on the facility containment tank.

In addition to recovered debris fragments, noteworthy data were obtained from AEDC, NASA, and Aerospace Corporation instrumentation. Video data and physical samples were used to identify the failure mechanisms from a hypervelocity impact. Debris fragments and high-speed video collected on the DebrisLV SUT were supplied to The Aerospace Corporation for analysis.

The combination of intellectual and physical resources allowed the Debrisat test project to provide exceptional data to several aerospace organizations. These 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 Debrisat Program will fill in several knowledge gaps about orbital debris and hypervelocity impacts, the test data collected will also lead to new areas of research. The overview of the test configuration that is documented herein will hopefully provide a baseline for future hypervelocity research, development, test and evaluation so that new efforts can be performed in a timely and efficient manner.

5.0 SUMMARY

The test project consisted of three hypervelocity impact tests that were successfully conducted between 25 February 2014 and 15 April 2014 at Hypervelocity Test Range G at Arnold Air Force Base, TN. During this test series, a scale multishock shield, a representative low earth orbit mock upper stage with tank and roll control assembly, and an LEO satellite were destroyed. The representative SUT were custom built to closely resemble their flight ready counterparts. The test utilized an approximately 600-gm projectile traveling just under 7 km/sec in a test environment of less than 2 torr. The fragmentation debris was collected using a calibrated soft catch for analysis to determine individual fragmentation characteristics. The resulting analysis from the fragmentation debris will be used to update modeling efforts.

Range G was the only ground-test facility that had the capability to accelerate a large mass to a velocity near 7km/sec to attain the impact energy required for the Debrisat Program. The last major satellite impact study was the SOCIT Program that was tested at Range G in 1992. Since that program the launcher was upgraded to an 84-mm bore configuration that is cable of launching more mass at higher velocities. The 1992 SOCIT test provided an impact energy to target mass ratio of 78 J/g. The Debrisat impact occurred at 235 J/g, a 300% increase over SOCIT due to improvements made to the AEDC Hypervelocity Flyout, Impact and Lethality Ground Test and Evaluation capability.

REFERENCES

1. Liou, J. C. and et al., "Successful Hypervelocity Impacts of DebrisLV and DebriSat," NASA Orbital Debris Quarterly News, Vol. 18, No. 3, 2014.
2. Rushing, R. and Roebuck, B. "Surviving the Space Junkyard: Using a Hypervelocity Ballistic Range to Assess Orbital Debris Impacts," AIAA 2010-8862, 2010.
3. Cunningham, T. "SOCIT Series Plan," General Research Corp. CR-91-1251, 1991.
4. Christiansen, E., Davis, A., Miller, J. and Lear, D. "Hypervelocity Impact Test with Large Mass Projectile," NASA Orbital Debris Quarterly News, Vol. 18, No. 2, 2014.
5. Sugita, S. and Schultz, P. H. "Spectroscopic Characterization of Hypervelocity Jetting: Comparison with a Standard Theory," Vol. 104, No. E12, pp. 30,825-39,845, December 1999.
6. Adams, P. M, Sheaffer, P. M. and Radhakrishnan, G., "FTIR Analyses of Hypervelocity Impact Deposits: DebriSat Tests," Aerospace Technical Operating Report No. TOR-2014, 2014.

APPENDIX A. TEST INSTRUMENTATION

Instrument	Organization	Description	Purpose/Comments
150 kV Flash X-ray	AEDC	Dual-headed, orthogonally-mounted x-ray system.	Determined exact projectile position for velocity calculations and ensured 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; 3 Phantom v711 cameras; 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 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 μm – 5 μm band	Captured infrared video of the postimpact environment.
AERHy Infrared Hyperspectral Imager (Spectrometer)	The Aerospace Corporation	1K–3K frames per second. Spectral range from 1.25 – 4.0 μm in one axis (600 spectral bins) x 128 spatial bins; 1.0-0.5 milliradians per spatial pixel.	Documented chemical signatures in infrared range.
Portable Mass Spectrometer	The Aerospace Corporation		Collected data on gases released from impact and late time reaction products.
Witness Plate Assemblies	The Aerospace Corporation	Aluminum plate with embedded quartz, sapphire, and adhesive coupons	Collected condensable species to investigate fragment darkening as result of interaction with impact gasses and plasma.

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. 1 Controller per ICCD for trigger control. SRS delay generator.	Recorded spectrally and temporally resolved signatures of the plasma flash. 3-m optical fiber was used to couple flash into spectrometer. Two 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	Nondestructive infrared analysis of samples	Posttest 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 pretest and posttest shots.

APPENDIX B. SOFT CATCH FOAM CONFIGURATION

