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T. Chaloupka, G. Crawford, M. Crumpler, B. Stephens
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231 Leach Center
Auburn University, Alabama 36849-5320

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ABSTRACT

At Auburn University's Space Power Institute (SPI), researchers have developed an affordable technique to duplicate the types of impacts observed on spacecraft, including the Shuttle. The SPI team has certified a Hypervelocity Impact Facility (HIF) which propels particulates using capacitor-driven electric gun techniques. The fully operational facility provides a flux of particles in the 10-100 micron diameter range with a velocity distribution covering the space debris and interplanetary dust particle environment (in the range of 3 to 13 km/s). Measurements made in the HIF of particle size, composition, impact angle, and velocity distribution indicate that all such parameters can be controlled in a specified, tailored test designed for or by the user. Unique diagnostics enable researchers to fully describe the impact, providing an evaluation of the "targets." while under full power or load. In this facility, industrial users regularly evaluate space hardware, including solar cells, coatings, and materials, exposing selected portions of space-qualified items to a wide range of impact events and environmental conditions. Benefits to industrial and DOD users include corroboration of data obtained from impact events, flight simulation of designs intended for space, accelerated aging of systems, and development of manufacturing techniques. In a series of HIF experimental shots, researchers duplicate, at modest cost, many years of accumulated space debris damage on spacecraft systems. This HIF is a true "gun for hire!"

INTRODUCTION

The SPI's hypervelocity impact facility was initially placed into service in mid-1991 with a NASA grant. Its purpose was to study the effects of impacts upon space materials, coatings, and power systems under development by NASA. The facility's capabilities have grown, along with the experience of its designers, to a point where the "gun" now possesses a capability to conduct micro meteoroid and micro particle debris impact effects studies tailored to the needs of individual users. It has been noted that man-made debris is prevalent in certain orbits and altitudes as a result of man's frequent use of those regimes to maintain and maneuver satellite systems. Some researchers contend that impact effects of man-made debris may be distinguished from cosmic particulate effects (1). Additionally, hypervelocity impacts by micro particles are potential initiators of electrical breakdown of space systems. Several sources have compiled over 50 recorded instances of failure and the most probable causes for failure. Many of those failures have been the result of spacecraft charging and discharging phenomena and debris impact (2). The breakdown/structural damage problem occurs as a result of the relatively enormous amount of energy released at the moment of impact of the micro particle with a satellite subsystem (Figure 3). The kinetic energy of micro particles create extensive damage, far in excess of particle dimensions or mass. This physical phenomena is discussed in Reference 3, including a discussion of impact-induced micro-plasma production and its negative effects upon high voltage power systems in LEO. Ultimately, a safe, accurate, low-cost, and predictably repeatable mechanism was needed to simulate the micro meteoroid damage scenario in the laboratory. With financial assistance from NASA and user contracts, Auburn's "gun for hire" was developed to meet an emerging space research requirement.

DISCUSSION

Description of Facility & Capabilities

Overview. The Auburn HIF is one of two in the world with the capability to accelerate micro particles, the other being located in Hahn, Germany. The Auburn facility is unique in several respects. It launches 20 - 50 micro particles at a time, ensures multiple impacts per shot, operates as a plasma drag device, and is exceptionally "clean." In general, the facility is best utilized with planar target specimens, although curved surfaces have been impacted and the impact craters evaluated with some measurable success. Special imaging techniques were designed and incorporated into the diagnostic suite for those curved surfaces. The HIF technique of acceleration has several advantages over existing hypervelocity impact techniques, namely,

- It can accelerate multiple projectiles in a single shot, thus producing an "aging effect" due to multiple damage sites.

- It can fire multiple shots without breaking vacuum on the specimen, enhancing the aging effect and reducing the time before test firings.

- Specially-designed diagnostics allow the researchers to identify individual impact sites and related velocities of impact.

- SEM/EDX analyses are done routinely for users.

- *Shots are tailored to the specific needs of the* user.

Facility Description. The target chamber is spacious, measuring 1.45 meter in diameter by 2.0 meters in length. Large set-ups are possible, including examination of powered subsystems operating in a LEO environment just prior to impact. There are numerous diagnostic ports, instrument feed-through stations, and specimen assembly racks. Both stainless steel chambers, the launcher and target chambers, may be pumped down independently, and even operated as separate test facilities if the need arises. The primary advantage of the two chambers is that it allows reconfiguration or rebuilding of the gun firing mechanism (launcher) without the disadvantage of breaking vacuum on the target chamber. This feature permits multiple shots against a single specimen target.

Operation. The HIF utilizes the thermal expansion of a plasma to accelerate micro particles in the size range 10µm - 400µm diameter. The system is described in detail elsewhere along with its typical operational sequence [4]. The plasma exit velocity at the muzzle has been measured at velocities in excess of 40 km/s using high-speed photographic techniques (IMACON 790 image converter camera). The resultant velocity distribution of micro-particles is dependent on the combination of stored energy, particle size and density, and the number of particles under acceleration. The launcher is housed in a vacuum chamber pumped to a pressure of $\sim10^{-6}$ torr ($=1.33\times10^{-4}$ Pa). The micro particles and residual launcher-drive gas pass along a 6.75m long flight tube to the larger evacuated ($\sim10^{-6}$ torr) chamber where they are allowed to impact the target specimen or system under test. Electrical isolation is achieved by the fact that all gun electrical activity has subsided before particle impact occurs in the target chamber. Furthermore, the hot plasma drive has relaxed and cooled and is captured by a series of baffles placed in the flight line. As a result, cleanliness is exceptional for a launcher system of this type. A final pre-impact baffle with an aperture correctly sized and positioned to control the impact site location may be inserted into the flight line. Masks are sometimes employed to provide "control" specimens or surfaces.

Diagnostics. The primary diagnostic for these tests is a Hadland-Photonics IMACON 790 Image Converter Camera. The IMACON is utilized in streak mode to detect the incident micro particles velocities and locations by virtue of the luminous impact-induced micro-plasma. This micro-plasma is viewed by the IMACON, looking parallel to the target surface, via a slit that limits the field-of-view (FoV) to no more than 100µm at the target surface (Figure 1). The camera is triggered to begin imaging at the time of launch of the particles. The arrival of each hypervelocity particle produces a light flash on the photographic image with a horizontal (time-axis) displacement proportional to the impact velocity. Since the flight distance is known to be 7.05±0.05m the velocity may be calculated from the time-of-flight. Impact site location is derived from the vertical displacement of the flash on the streaked photographic image of the slit. Each impact produces two flash images, one displaced positively, the other displaced negatively, from the image horizontal center-line. Light emitting diodes (LEDs) are placed at known positions such that their continuous images provide boundaries on the photographic image corresponding to the impact zone limits.

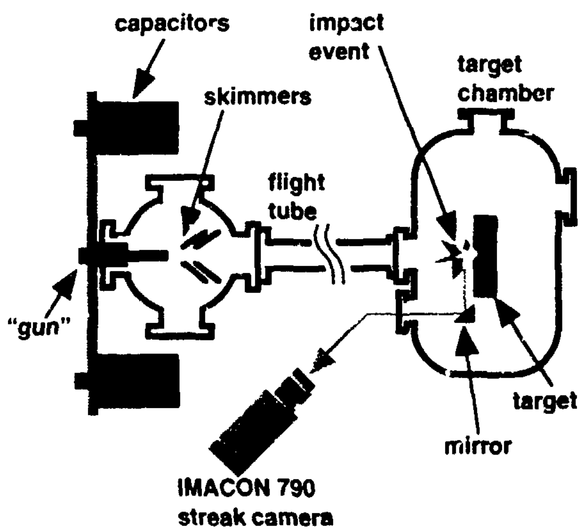

Figure 1. Schematic of Hypervelocity Impact Facility

Capabilities Description. The HIF has the following special attributes which make it unique and ideal for the study of impact and impact-induced phenomena:

- Utilizes plasma drag phenomena to produce a particle stream with minimal break-up and a wide range of velocities in a single experiment.
- Accelerates a wide range of materials successfully.
- Enables user to study accelerated aging through multiple impacts without breaking vacuum.
- Operates with an advanced diagnostics suite capable of tracking and completely characterizing up to 50 particles in a single experiment.
- Provides a clean experiment in that accelerator-produced debris is minimal and identifiable
- Offers the flexibility of three experiments per day.
- Offers a large target chamber to accommodate fully functioning spacecraft components while under a variety of space stimuli such as ultraviolet radiation, atomic oxygen, space plasma, and micro particles.
- Equipped with 40 channels of electrical diagnostics, some with a bandwidth of 500 Mhz.

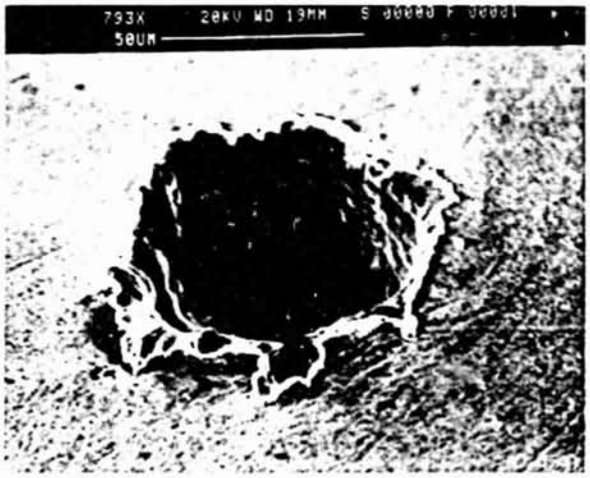

Figure 2. Crater created in a copper target by an olivine micro-particle travelling at between 10-11 km/s at an angle of 45°. Note the deep crater structure, even at such an oblique angle, and the pronounced crater lip.

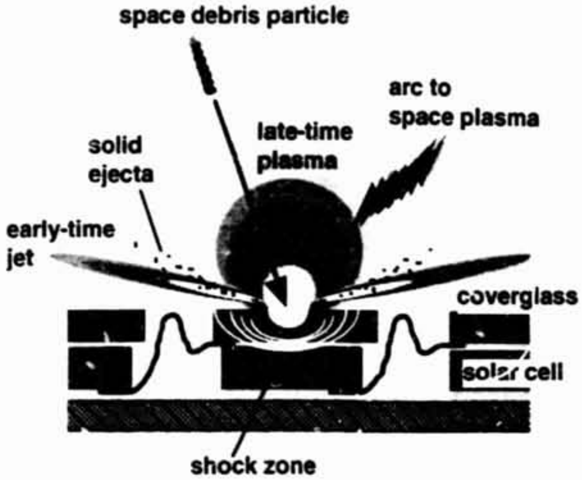

Figure 3. Schematic of hypervelocity impact on a solar cell. Note the emission of copious amounts of ejecta which can interact with the local ambient space environment.

General Test Protocol. After a significantly large number of shots (in the hundreds), the SPI research team has successfully combined its "lessons learned" and various user requests into a packaged set of research capabilities for the HIF (discussed above). A rigorous test protocol was developed and implemented nearly two years ago. This milestone has led to continual incremental improvements in the facility's performance. SPI researchers have demonstrated that accelerated life testing is a necessity in order to study system survivability and degraded system performance as a result of impacts, as well as to study system reliability and failure modes. *These determinations can be made through HIF testing, at reduced cost, and with no risk to space mission/launch equipment and personnel. Tests currently being conducted for users from industry and government laboratories have included an analysis of particle craters, particle velocities for identifiable impact sites, qualitative damage analyses, and video documentation of damage to space systems.*

Typical Research on Space Systems. In one particular research effort (for NASA Langley), the SPI team conducted experiments on the effects of impact angles on crater morphology and impactor residue retention as a result of hypervelocity impacts upon selected target materials (5). The study of impact angles which were 30, 45, 60, and 75 degrees from the particle flight path showed some interesting results. First, in the case of the 30 and 45-degree angles, researchers concluded that the craters were almost identical to normal incidence

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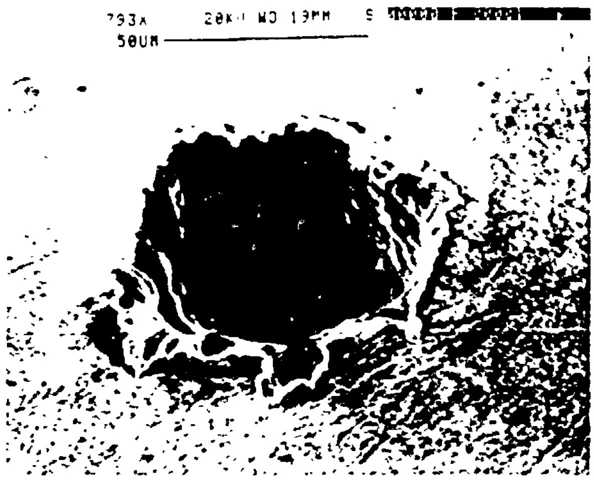

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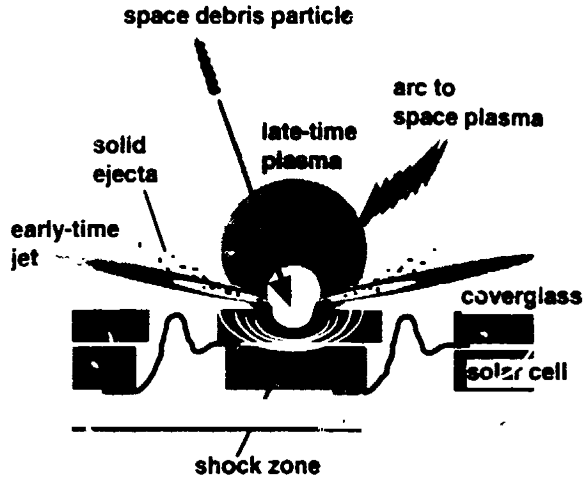

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<u>Typical Data Obtained from Tests</u>. Figure 4 illustrates typical data taken from a series of NASA-initiated tests on an anodized aluminum plate designed for space station use. The data depicts typical crater dimensions for a total of 31 silicon carbide micro particles. The velocity distribution varies from 1 to 12 km/s for these particles.

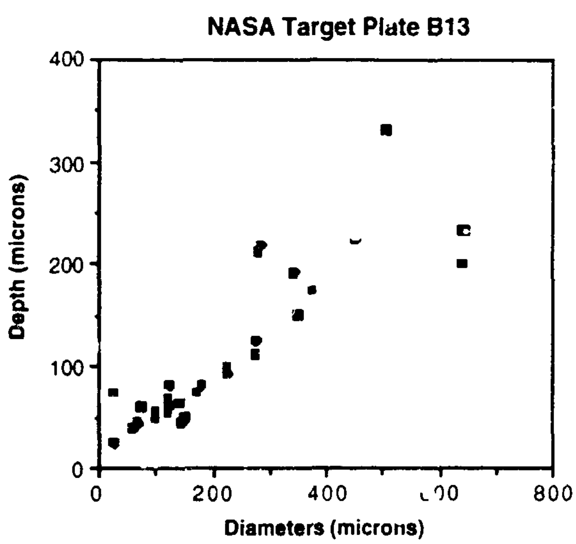

Figure 4. Illustration of a typical distribution of crater dimensions from a total of 31 impact events produced by 75 micron SiC particles impacting upon an anodized aluminum plate.

The number of particles may be controlled by the configuration of the gun plate, the armature load, and the diameter of the conical skimmers mounted in the flight tube to collimate the particle stream. Using the crater's dimensions, a particle's velocity measured by a streak camera, previously determined scaling laws (6), and the materials parameters of the target and projectile (particle), the research team may calculate the impacting particles' dimensions as verification of the dimensions loaded at the start of the firing sequence. There has been excellent agreement between the initial particle dimensions and those calculated from impact sites. There is, admittedly, some particle breakup due to acceleration forces after the armature fires.

<u>Test and Data Analysis -- the Cost</u>. Rates for a tailored series of shots in the facility are subject to a number of factors. For example, the cost range for individual shots is usually calculated by incorporating the time required for set-up, the amount of special machining required for test apparati and fixtures, the number of man-hours expected to be devoted to the entire test sequence, the amount of post-impact analysis required, the complexity of the pre-impact facility preparation (ensuring that the exact velocity regime for the type and number of particles requested by the user can be met), and the total number of shots in the series. At current rates, average costs vary from the "bare bones" figure of $1700/shot to the "full up" figure of $3200/shot, depending upon the inclusion of university indirect costs. "Average costs" quoted here are strictly estimates based upon current operating expenses, materials costs, current man-hour costs, the analysis protocol required by the individual user, the exact test series negotiated by the user with Auburn University, and, in some cases, the published indirect cost planning factors for Auburn University. Discounts could be negotiated for large numbers of shots.

<u>Test & Evaluation Capability</u>. Because of the superior data analysis and evaluation facility at the Institute, the SPI research team has also evaluated the condition of solar photo voltaic electrical components flown on the Long Duration Exposure Facility (LDEF) as part of the Solar Array Materials Passive Experiment (AO-171). LDEF spent nearly six years in LEO. Nine countries contributed 57 experiments to the research project which was originally launched in 1984 to study the long term effects from the harsh space environment. Similar hypervelocity impact tests have been made against NASA solar array modules intended for Space

Station applications (Figure 5). Researchers explain that the data being gathered from these projects is primarily applicable to improving spacecraft designs and has significant value to LEO satellite technologies (7). It is anticipated that potential facility users will emerge from the communications satellite group in the near future.

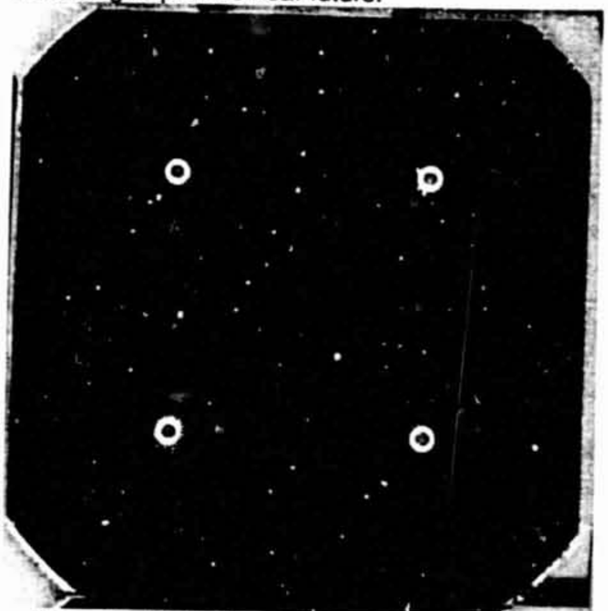

Figure 5. NASA Space Station Solar Cells After Impact Testing in HIF

Planned Facility Improvements. The SPI is presently seeking funds to increase the upper limit of the velocity regime to 20 km/s (from 13 km/s). Those modifications are planned to be completed within the next 24 months. Other accompanying improvements may be required in the data collection and analysis procedures as a result of this enhancement of the upper velocity limit.

Current Users of the Facility

An Industry Work Horse. Users of the facility have ranged through industries with materials or sub-systems intended for space flight applications. Boeing, Rockwell, Martin-Marietta, and TRW are frequent users, each studying specific space system components such as optics, optical materials and surfaces, or solar cells. NASA Marshall Space Flight Center has investigated optics, coatings, and solar array components for such qualities as durability, accelerated aging due to impacts, and degradation of performance as a result of strategic penetrations by micro particles. Those tests were conducted in a plasma environment with electrically-biased components. Other users, in the academic sector, include space technologists from the University of Toronto, who has been collaborating with Auburn University in studying carbon composite structures attacked by hypervelocity micro particles and the related effects of atomic oxygen attack after micro particle impact damage. The Institute for Space Science and Technology (Gainesville, Florida) has conducted hypervelocity impact tests on impact resistant materials, as well as a post-flight calibration check for an application of metal-oxide-silicon impact detectors. Government agency interest, particularly by the Defense Nuclear Agency and NASA Langley, has centered on studies of electrical breakdown anomalies and effects. As stated earlier, NASA Langley investigators are also collecting data on the significance of the angles of impact by micro particles, and Institute researchers have published a preliminary report on the significance of micro particle impact angles. Follow-on studies are planned with new materials.

Potential Users -- An Opportunity. Potential users for this unique facility include industries and space component designers who are interested in studying the effects of impacts from high speed micro particles upon composite materials, nose cone materials, ceramics, protective films, electronic components damaged while under electrical load, and communications satellite components. Figure 6 illustrates a new research opportunity -- the study of new coatings such as polycrystalline diamond-coated substrates. As shown, some impact testing is being done on diamond-film coated substrates.

Figure 6. Scanning electron micrograph of the typical crater structure formed by a 100 micron olivine particle impacting on a polycrystalline diamond-coated scratched silicon substrate. Crater diameter is 82 microns.

SUMMARY

In summary, the hypervelocity impact facility located within the Space Power Institute at Auburn University is being contracted out to industry and government lab users on a space available basis. The facility is well-equipped to provide data on many phenomena associated with impacts on spacecraft and those materials used in their construction. The facility possesses many special attributes which enable its hypervelocity impact tests to be tailored for specific user needs. The research team assigned to operate this facility is highly experienced and solely dedicated to the H - and its study of impacts and impact-induced phenomena. *The facility is flexible in its set-up, capable of completing multiple shots per day, versatile in accelerating various t_ ɲes and sizes of materials, and expert at delivering the required velocities to the target plate in a single experiment.* In effect, it provides researchers with a capability to study aging effects by impacting target samples more than one time while not breaking a simulated space vacuum. Finally, the facility is large enough to accommodate a variety of fully-functioning spacecraft components or sub-systems while under a variety of space stimuli such as ultraviolet radiation, micro meteoroids, space plasma, and atomic oxygen.

ACKNOWLEDGMENTS

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