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HYPERVELOCITY IMPACT FACILITY FOR SIMULATING MATERIALS EXPOSURE TO IMPACT BY SPACE DEBRIS

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ABSTRACT

As a result of man's venturing into space, the local debris contributed by his presence exceeds, at some orbital altitudes, that of the natural component. Man's contribution ranges from fuel residue to large derelect satellites weighing many kilograms. Current debris models are able to predict the growth of the problem and suggest that spacecraft must employ armor or bumper shields for some orbital altitudes now and that the problem will become worse as a function of time. The practical upper limit to the velocity distribution is on the order of 40 km/sec and is associated with the natural environment. The maximum velocity of the man-made component is in the 14-16 km/sec range. The long duration exposure facility (LDEF) has verified that the "high probability of impact" particles are in the microgram to milligram range. These particles can have very significant effects on coatings, insulators, and thin metallic layers. The surface of thick materials becomes pitted and the local debris component is enhanced by ejecta from the impact events. In this paper, a facility is described which produces a reasonable simulation of the space debris spectrum in a controlled environment. The facility capability is discussed in terms of drive geometry, energetics, velocity distribution, diagnostics, and projectile/debris loading. The facility is currently being used to study impact phenomena on Space Station Freedom's solar array structure, other solar array materials, potential structural materials for use in the station, electrical breakdown in the space environment, and as a means of clarifying or duplicating the impact phenomena on the LDEF surfaces. The results of these experiments are described in terms of the mass/velocity distribution incident on selected samples, crater dynamics, and sample geometry.

INTRODUCTION

In addition to the natural space micrometeoroid environment, the constant injection by man of a non-natural component has led to additional concern. This "space pollution" has accelerated due to the steadily increasing frequency of launches by the industrialized countries even though there is a growing awareness that the debris problem must be addressed. As other countries become active in space and if space concepts such as those envisioned by the SDI are deployed, it is inevitable that future spacecraft will have to devote a substantial mass fraction to the armoring of critical components. Further, hypervelocity impact produced debris and plasma can trigger electrical breakdown and further reduce the effectiveness of insulators for space use. For the most favored low-to-medium earth orbits it is projected from some models [1] that significant design changes will be necessary by the year 2000. At geosynchronous orbits the problem would be a design driver not too many years thereafter.

The LDEF experiment clearly shows that over its limited time in space there were no structurally catastrophic hits. [2] There were, however, enormous numbers of impacts which could have effected solar arrays, transmission lines, optical and thermal coatings, and protective coatings used to shield against atomic oxygen and the effects of ultraviolet radiation. The analysis to date has shown that the damage produced is synergistic with other space environmental factors such as atomic oxygen and ultraviolet radiation. [3] By far, the preponderance of impacts are particles with masses in the microgram to milligram range over the entire velocity spectrum. Further, the analysis indicates both natural and abundant "man-made" sources of debris.

There are a number of options [4] for studying space impact phenomena. First, and perhaps most expensive is to place suitable materials in space for the requisite period of time. This is a "specialized long-term LDEF" approach and should be a part of any future LDEF experiment. The second quick-response approach is to use light gas gun technology to accelerate macro-projectiles in the gram range for impact studies. Due to the hydrodynamics of staged, compressed light gas guns, the velocity limit is about 10 km/sec and is unsuited to accelerating particles with the LDEF experimental profile. Further, unless judiciously designed, massive unwanted debris from the seals and sabots and the "large gas slug" also will impact the sample. As a result, it is difficult to do experiments on active systems or "mock ups" designed to simulate active spacecraft components. The third technique is to employ "electromagnetic accelerators" [5] to drive suitable projectiles in a vacuum chamber to more closely duplicate the space environment as well as inflict minimum additional damage to a sample.

EXPERIMENTAL DESCRIPTION

Figure 1 shows a block and schematic diagram of the electrical drives for an accelerator capable of driving small projectiles to hypervelocity.

The capacitor bank consists of a four segment bank with total capacitance of 53.6 microfarads storing some 67 kilojoules at a maximum charging potential of 50 kV. The desired experimental capacitor voltage is achieved by a high voltage power supply charging the capacitor bank through an appropriate charging resistor designed to limit the charging rate. In the event of a misfire, a suitable array of protective circuits and "dummy load resistors" are provided to discharge the bank. Once the desired voltage has been reached, the closing switch is triggered resulting in a current pulse of some 1 million to 1.5 million amperes flowing through the exploding foil driver. The current rise time is governed by external circuit inductance and is on the order of 200 ns.

The foil assembly rapidly explodes producing an extremely hot metallic plasma which is accelerated due to $\bar{J} \times \bar{B}$ forces and internal pressure from the explosion byproducts. The contacts to the assembly are constructed of stainless steel and, due to the enormous dynamic forces, are constrained by an insulating structure composed of high strength composite. The entire assembly is fastened to a high current feed-through plate.

Particulate suitable for impact studies can be generated by a number of techniques. The foil assembly itself is a source of ultra small particles and for this system these particles are aluminum. Secondly, the enormous currents generated by the discharge have a tendency to ablate particles from the stainless steel contacts and thirdly, an ablator plate, suitably loaded with fragments, can be designed to provide the vast majority of the fragments in a controlled way.

Figure 2 shows the design of an armature package typical of that used in this facility.

As the aluminum foil explodes, the hot plasma totally decomposes the plastic ablator plate into constituent gasses such as hydrogen and carbon at a temperature of several thousand degrees K. This plasma/gas slug/debris package is accelerated further down the drift tube both by $\bar{J} \times \bar{B}$ forces and due to the hydrostatic pressure generated by the hot gases. As a result, the microprojectiles are "dragged along" at a substantial fraction of the plasma velocity. The plasma/debris cloud velocity has been measured by high speed photography to be greater than 40 km/sec. Obviously, loading of the armature assembly with a selected particle size and mass determine the velocity distribution of the particles and, clearly, not all particles will have the same velocity.

Figure 3 shows the vacuum chambers and flight tube geometry for the facility. The first chamber holds the gun, high current feed-through and an experimental impact station. The chamber has four

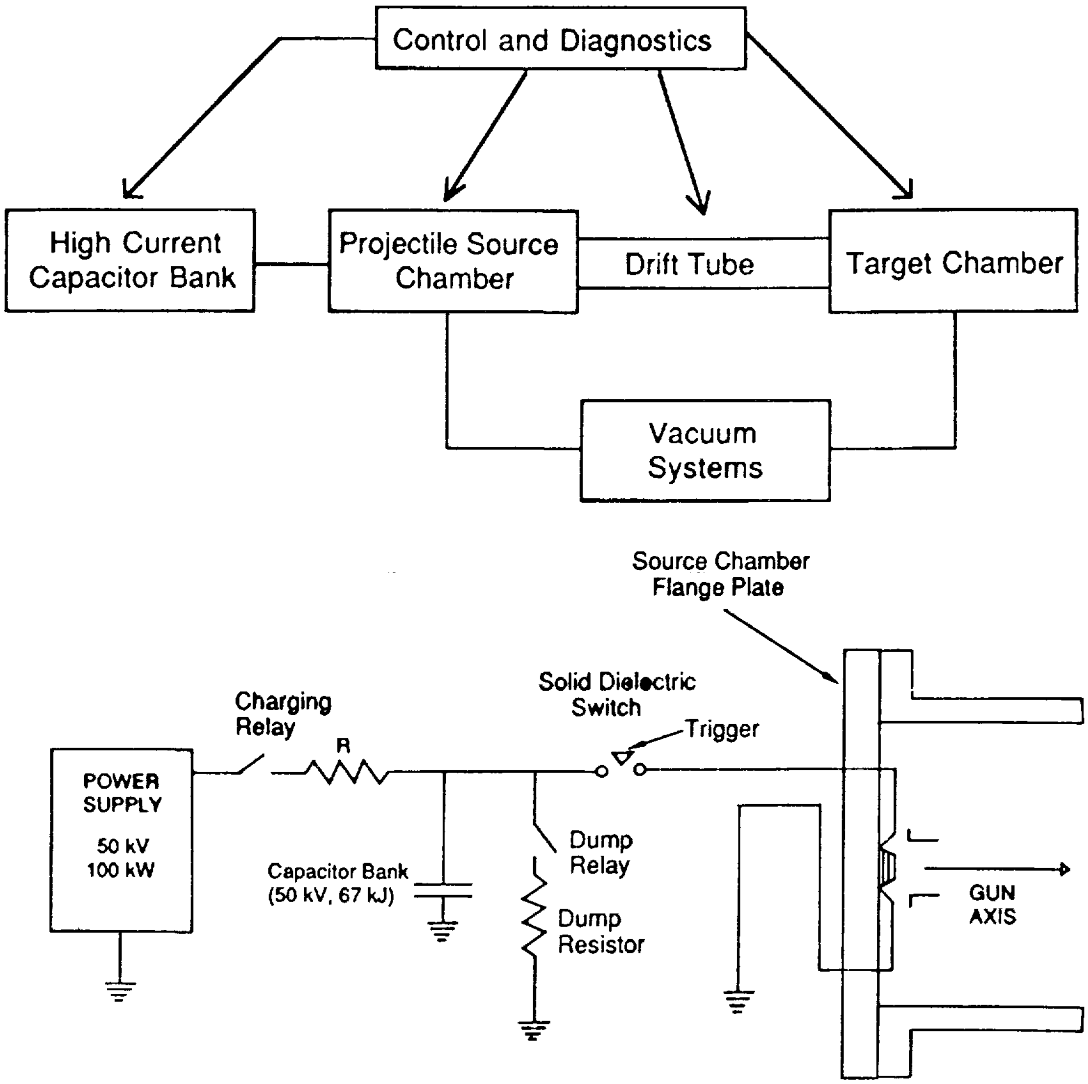


Figure 1. Block and schematic diagram of the facility and the gun drive circuits.

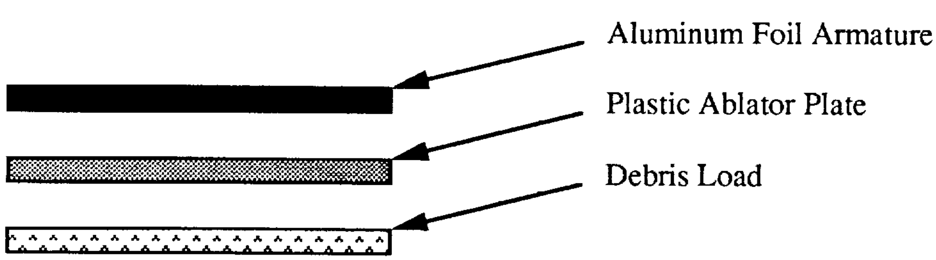


Figure 2. Projectile/debris assembly showing separate components.

viewing ports and several diagnostic feed-through flanges for use as needed. In addition, conical skimmers can be placed in this area to allow gas diversion and particle beam selection for propagation down the drift

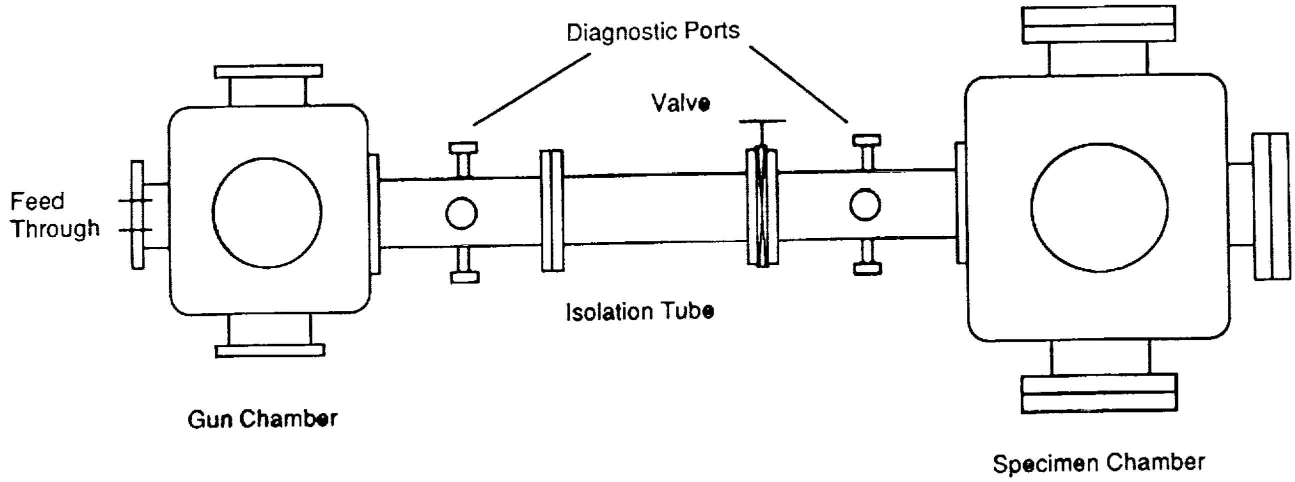


Figure 3. Vacuum chambers for hypervelocity facility.

tube. The chamber has its own pumping and diagnostic station. The maximum chamber diameter is 36 cm and along the flight axis allows about 1 meter of linear experimental space within the beam line.

The second chamber, the major impact/specimen chamber, is 1.45 meter in diameter and 2 meters long. It has numerous diagnostic ports, instrument feed-through stations, and specimen assembly racks. It too is separately pumped and has its own diagnostic station. Both chambers are made from stainless steel and can be pumped to 10^{-6} torr.

The chambers are separated by a 6.75 meter (variable) flight tube which effectively allows all electrical activity due to gun firing to subside before impact occurs in the main chamber. Further, the hot expanding gases have been allowed to cool, to be trapped, and almost all of the "unwanted" armature residue captured before striking the specimen located in the main chamber. To facilitate the diversion of unwanted gas and gun debris, additional skimmers are placed in the flight tube. The chambers are isolated by a suitable valve allowing the gun to be reworked without disturbing the experiment in the main chamber. In this mode, operational systems or semi-operational subsystems can be exposed repeatedly without returning to atmospheric pressure. The main chamber feedthroughs and Institute power capability allow for as much as 100 kW DC power to be supplied to the main chamber as needed.

It is extremely difficult to diagnose the velocity of a particulate stream moving at hypervelocity. The drift tube contains a six-port for diagnostic purposes. One set of ports are used to provide three "optical curtains" which can be produced by high intensity lights or by lasers. The "other set of ports" are fitted with sensitive photomultiplier tubes to look for scattered light from the passing particulate beam. The flight tube is segmented in a number of places allowing the six-port to be placed to minimize electromagnetic interference and residual illumination from the expanding drive products. The ability of this technique to resolve particulate matter is a function of the particle size, its velocity, the width of the optical curtains, particle scattering cross-section, optical intensity, and the sensitivity of the detector system. We have successfully resolved velocities on the order of 20 km/sec for particles of unknown size. In general, the diagnostic station is placed as far away from the drive section as possible to allow time of flight to produce an adequate particle separation for particles with nearly the same velocity, since it is impossible to resolve particles entering the light curtain simultaneously.

There are two other diagnostic techniques used to characterize the particle beam. For those samples sufficiently robust, high bandwidth piezo sensors can be mounted on the back of the specimen to record time of arrival, and hence velocity, over a wide range of particle velocities. As with the optical curtains, this technique does not allow unambiguous localization of a specific impact event with a specific velocity. It does extend the velocity region to greater than 40 km/sec. The best technique to employ is a high speed image converter camera utilized in the streak mode. The experimental set-up and an example of an "impact event" is shown in Figure 4.

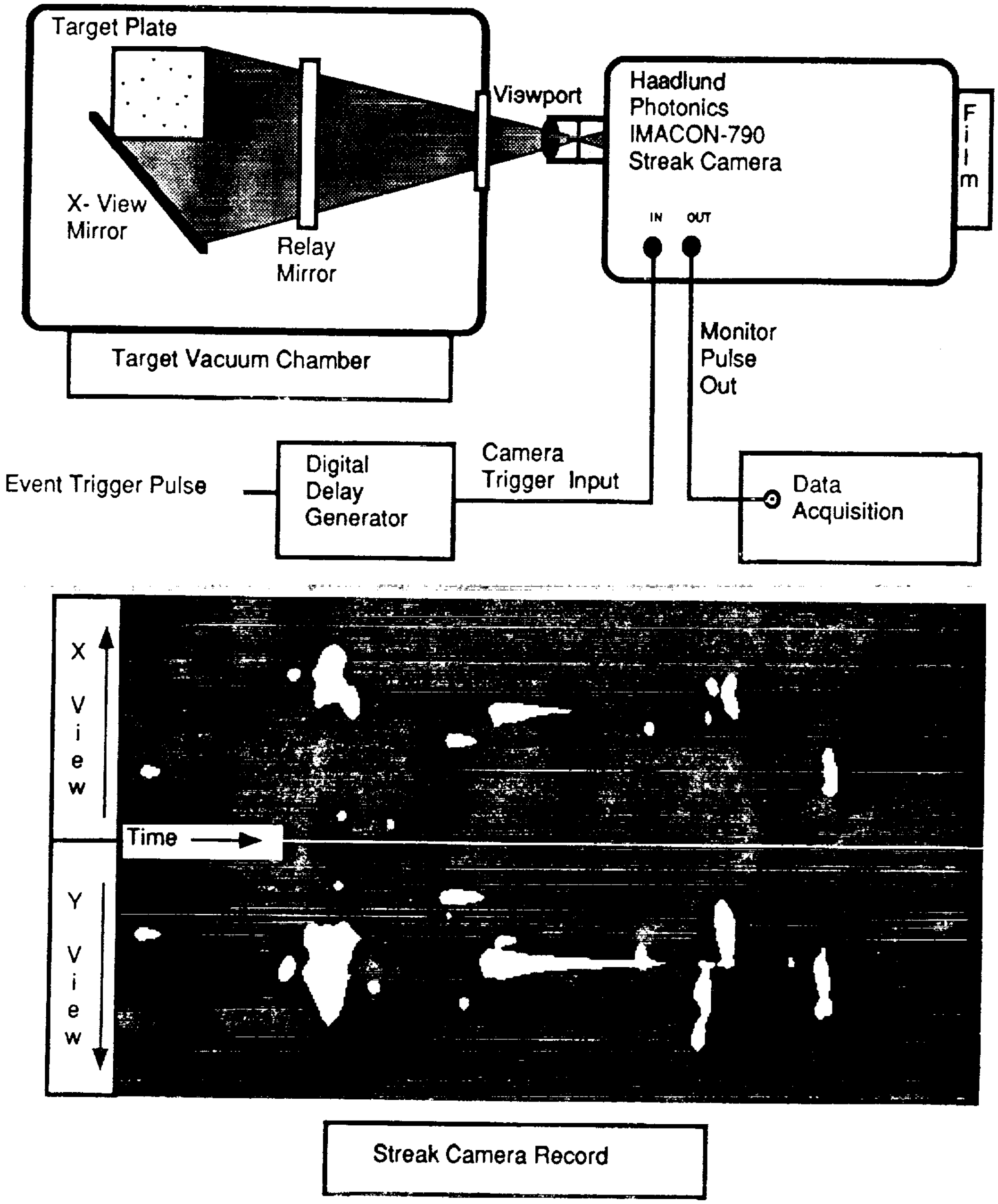


Figure 4. Streak camera diagnostic system schematic which allows both spatial location and velocity to be determined for each impact event.

Referring to Figure 4, a Haadlund high speed framing camera is used to monitor impact events due to the intense optical flash which occurs on impact. Using an optical lever the image slit is placed about 0.1 millimeters above the specimen plane in both directions. Both the x and y coordinate of any individual impact event can be directly measured from the streak record and the crater located precisely after applying an appropriate scale factor. Since the image is "streaked" across the film plane at a known rate, the position of the impact event on the film uniquely determines the velocity of the particle impacting the specimen. Modulated light emitting diodes are placed at the edges of the specimen to allow easy determination of the x-y coordinates and to facilitate in measuring the time of arrival. The camera is started after a suitable delay in order to improve resolution. This method is particularly suited to the measurement of particles which are moving at high velocities and produce highly luminous plasma clouds on impact. Within the limits of sensitivity of the film, plasma lifetime can be measured within the field of view and correlated with particle size, species, and velocity.

The streak camera record also contains information related to the ejecta cone angle. If the slit viewing plane is set many particle diameters above the impact sample surface (a few hundred microns), the assumption that the impact is a point source of light is valid. Measurement of the width of the luminous spot on the film provides a measure of the cone ejecta diameter at the location of the slit. One single streak image now contains information on:

- x, y coordinates of each impact,
- number of impacting particles,
- velocity of each particle,
- duration of optical flash,
- approximate cone angle of the ejecta.

The only remaining piece of information necessary to uniquely characterize the impact event is to have a unique measure of the particle size. If the particle is moving at a sufficiently high velocity, on striking an extremely thin target, the particle will penetrate, suffering almost no damage and leave a "footprint" characteristic of its dimensions. [6] In general, the characteristic particle dimension should be many times the thickness of the film and the velocity greater than 5 km/s. In this facility ballistic films made of plastics 0.9 microns in thickness are supported on a wire grid and placed on a holder about 6 cm above the specimen. The film and specimen share a common fiducial mark allowing an impact crater to be uniquely identified with a "footprint" on the ballistic film. The technique is shown in Figure 5.

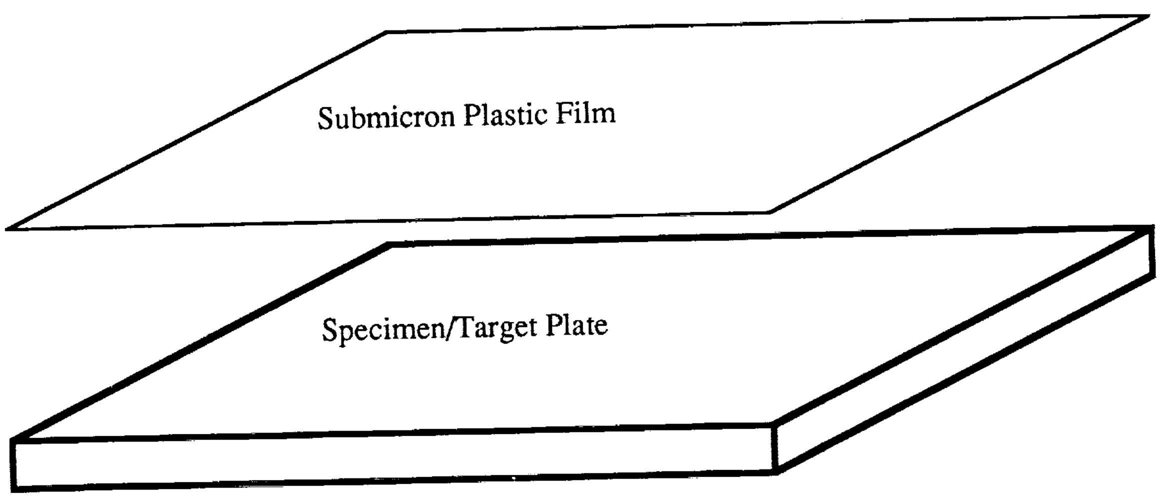


Figure 5. Ballistic film/specimen experimental arrangement.

In order to test the hypothesis that the ballistic film technique could be used to measure gun-induced breakup and particle size, the length (L) to width (W) ratio for nominal 100 micron aluminum oxide was measured. The average and deviation for 500 particles was 1.6 $\pm$ 0.5. Only 29 impact events were used to determine the L/W ratio for penetrations of the ballistic film. The L/W ratio was 1.98 $\pm$ 0.7. A correction factor for random orientation at penetration was also used. The lower limit in velocity for this experiment was on the order of 3 km/s which would leave a bigger footprint in the film. The absolute values in both L and W were comparable for the particles and the penetration "footprint." Additional data is being generated to improve the statistics and give more confidence in the technique. Our preliminary assessment is that there is little particle breakup during acceleration and that the ballistic film technique is valid to determine the approximate size for an impacting particle.

Figure 6 is a series of photographs to illustrate the total diagnostic technique. In the upper left hand corner is an electron micrograph of the nominal 100 micron aluminum oxide particles. The L/W ratio for

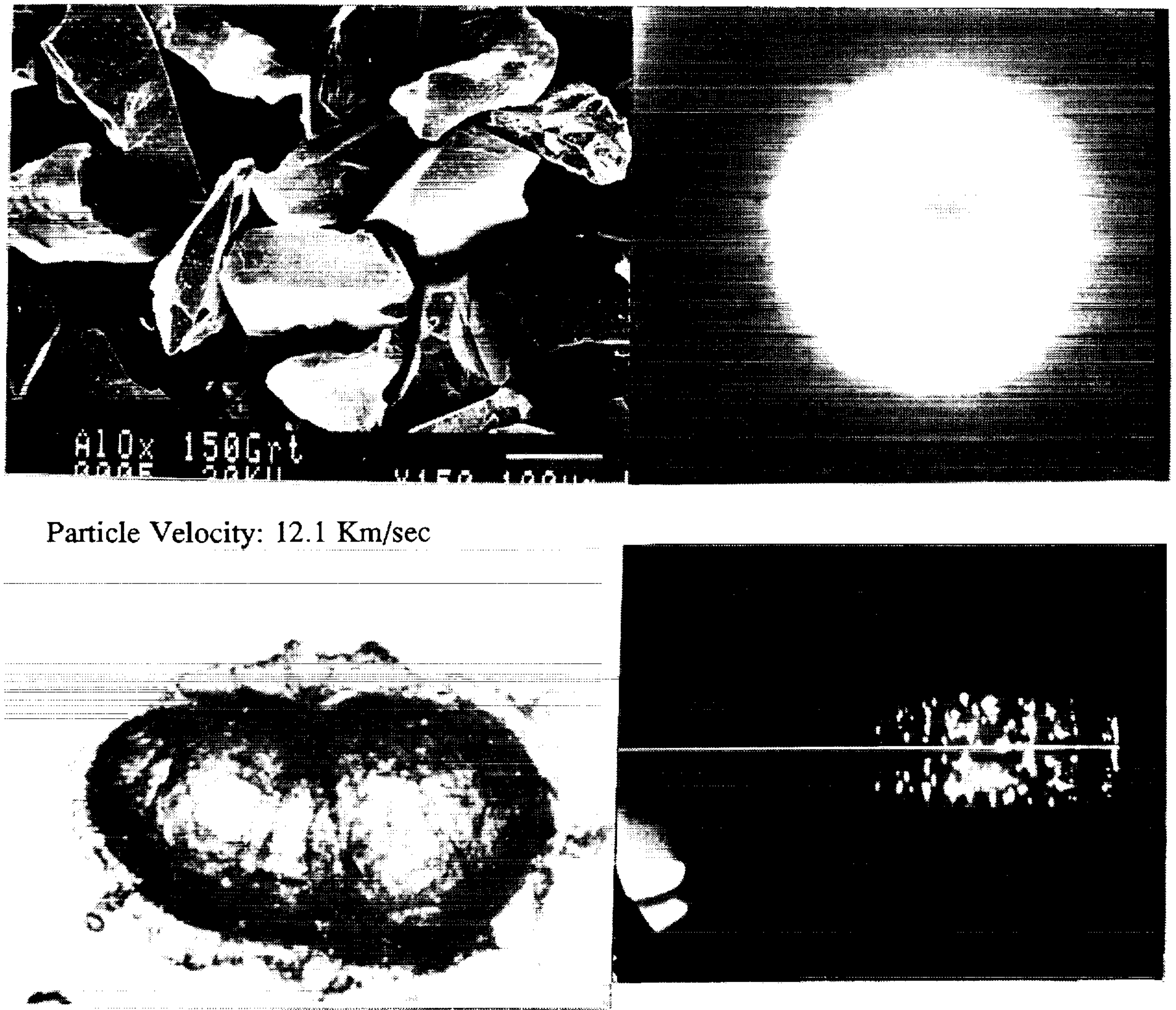
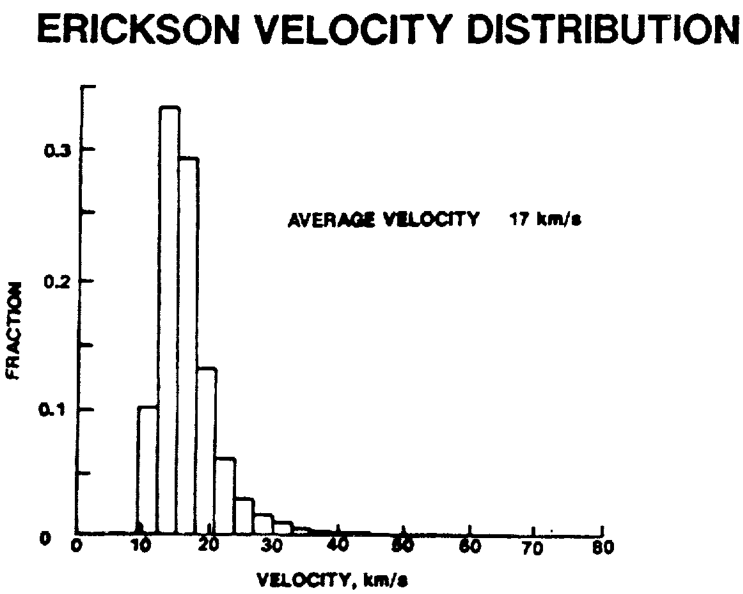


Figure 6. Collage of photographs illustrating the total diagnostic technique used in the hypervelocity facility.

some individual particles can be as big as 4. In the upper right hand corner, the "decorated footprint" made by one of the particles is shown. The photograph in the lower right hand corner is the impact crater formed in copper by the particle whose "footprint" is shown in the upper right hand corner of the figure. In the lower right hand corner is the streak record of all impact events in this experiment (3.0 km/s < V < 12.1 km/s). The impact event chosen for illustration was the fastest particle observed in the test and was moving at impact at a velocity of 12.1 km/s. There are some 55 particle impacts visible in this experiment. In general, it is hard to unambiguously resolve that many particles uniquely, especially near the center of the particle distribution.

Since the primary acceleration process is "plasma drag," there is always a gradient in the velocity of the particle stream. The maximum velocity obtainable and the velocity distribution are complex functions of the particle shape, particle density, absolute particle dimensions, and the gun parameters. Just as in space, there is always a wide range of particle velocities in a given experiment. From the point of view of simulation, this is desirable since it probably is a more accurate representation of the actual conditions in space. Figure 7 illustrates one of the many derived particle velocity distributions typical of the meteoroid flux in space.



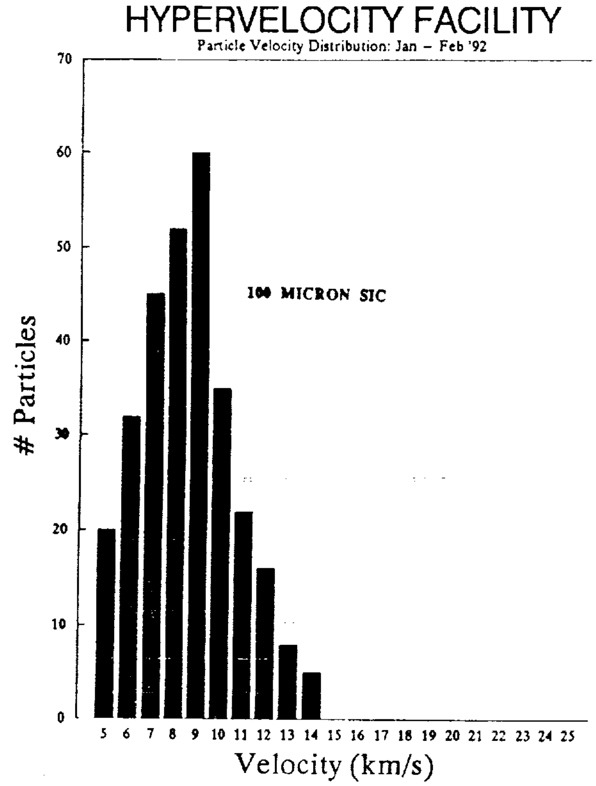


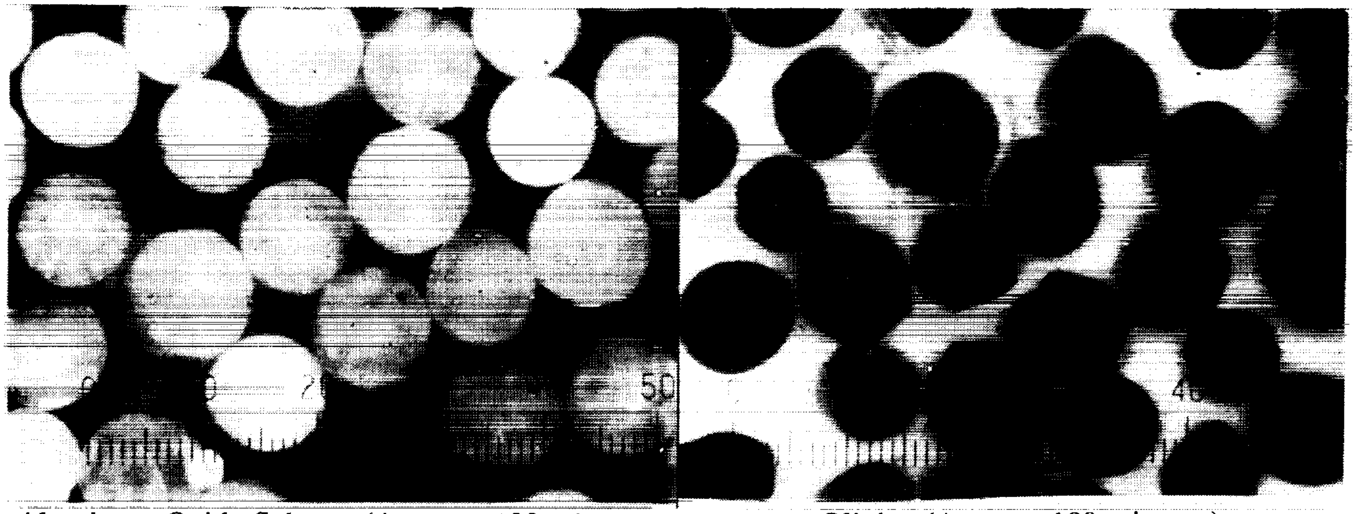
Figure 7. Velocity distribution postulated for meteoroids and the velocity distribution from the hypervelocity facility using nominal 100 micron silicon carbide particles.

Also shown in Figure 7 is an experimentally derived velocity distribution for nominal 100 micron silicon carbide particles. This distribution is based upon several experiments and while it does not duplicate the "Erickson distribution," it does overlap in the region of the distribution peak. Further, the particulate used in the facility is much larger than that typically seen on the LDEF experiments. We have collected experimental data on the velocity distribution for 400 micron and 100 micron aluminum oxide, and 100 micron olivines. The upper limit on the velocity distribution for 100 micron aluminum oxide is 11.5 km/s as compared to 14.5 km/s for the same size silicon carbide. This is to be expected since the density of aluminum oxide is roughly 1.2 times that of silicon carbide. At the moment, there is insufficient data to predict accurately the velocity distribution as a function of material and size.

In order to reduce the ambiguity in size, spheroidized olivine and aluminum oxide in a range of sizes from about 40 microns to greater than 100 microns have been fabricated. Figure 8 is an electron micrograph of the spheroidized particles. Unless requested otherwise, all future experiments in the facility will utilize these spheroidized particles for ease in determining gun performance from the ballistic film.

RESULTS AND DISCUSSION OF APPLICATIONS OF THE HYPERVELOCITY FACILITY

The facility is being used to study a variety of phenomena associated with hypervelocity impact. In the space plasma, dielectric coated surfaces can acquire a surface charge due to the electric currents in the spacecraft. [7] Without hypervelocity particle impact, the breakdown strength would be determined by the thickness of the coating and, in general, is several hundred volts. With hypervelocity particles destroying the dielectric layer, breakdown levels as low as -75 volts have been observed. The frequency of these events would depend on the meteoroid flux and the rate at which charge is trapped on the surface. Figure 9 illustrates impact events on dielectric/dielectric coated surfaces which produce craters many microns deep.



Aluminum Oxide Spheres (Approx. 100 microns) Olivine (Approx. 100 microns)

Figure 8. Spheroidized aluminum oxide and olivine particles for use in the hypervelocity accelerator.

The impact velocities were in the range of 8 - 12 km/sec and the particles consisted of nominal 100 micron silicon carbide. Figure 9a is an impact event on a thick painted aluminum surface. Note that the damage extends far beyond the central impact crater, a factor which must be taken into account when assessing the total effect of bombardment on surface properties. In addition, the area subject to atomic oxygen attack is several times the impact crater. In Figure 9b, a similar effect is seen in the impact area for kapton coated aluminum. Again, the damage due to film separation is several times the diameter of the impact crater. Figure 9c is an impact event which totally penetrated the woven thermal mat. The diameter of the hole is several times the particle dimension. The particle was totally destroyed on impact. Figure 9d is a typical impact on optical glass. The central impact zone is surrounded by a small damage zone several times the central region. The central region is highly fractured and shows some signs of melting. Evidence for extreme melting on optical materials was presented at this LDEF conference and it was judged that the particles were moving greater than 10 km/s on impact. For the event in Figure 9d, the particle velocity was about 8 km/s. These events are typical of the same phenomena witnessed on the LDEF surfaces and offer an excellent opportunity to duplicate and calibrate the data gathered from the various experiments on LDEF.

One of the more intriguing opportunities for analysis of the LDEF samples is to examine the crater sites for residue from the impacting particles. In space, there is ample opportunity for cross contamination due to debris from other impacts, outgassing from other materials on board, and due to terrestrial handling in a variety of modes. By studying these same phenomena in the hypervelocity facilities, tracer materials unique to the projectile can be used to study the residue as a function of impact velocity and location with respect to the impact site. Hypervelocity impact generates extremely high temperature which can totally vaporize the impacting particle in an explosive event with the resultant expulsion of almost all of the impacting particle mass. Using energy dispersive x-ray analysis, we have identified the contaminants which are produced as a result of the acceleration process. These are primarily aluminum, calcium, carbon, chlorine, iron, silicon, sulfur, and potassium. There are no measurable sources of magnesium in the materials used in the construction of the hypervelocity accelerator and the projectile assembly. As a result, the magnesium in the olivine projectile material can be used to trace the location of projectile debris in any impact event. Figure 10 is an electron micrograph of a crater formed by a nominal 100 micron olivine particle for an impact velocity of 8.9 km/s.

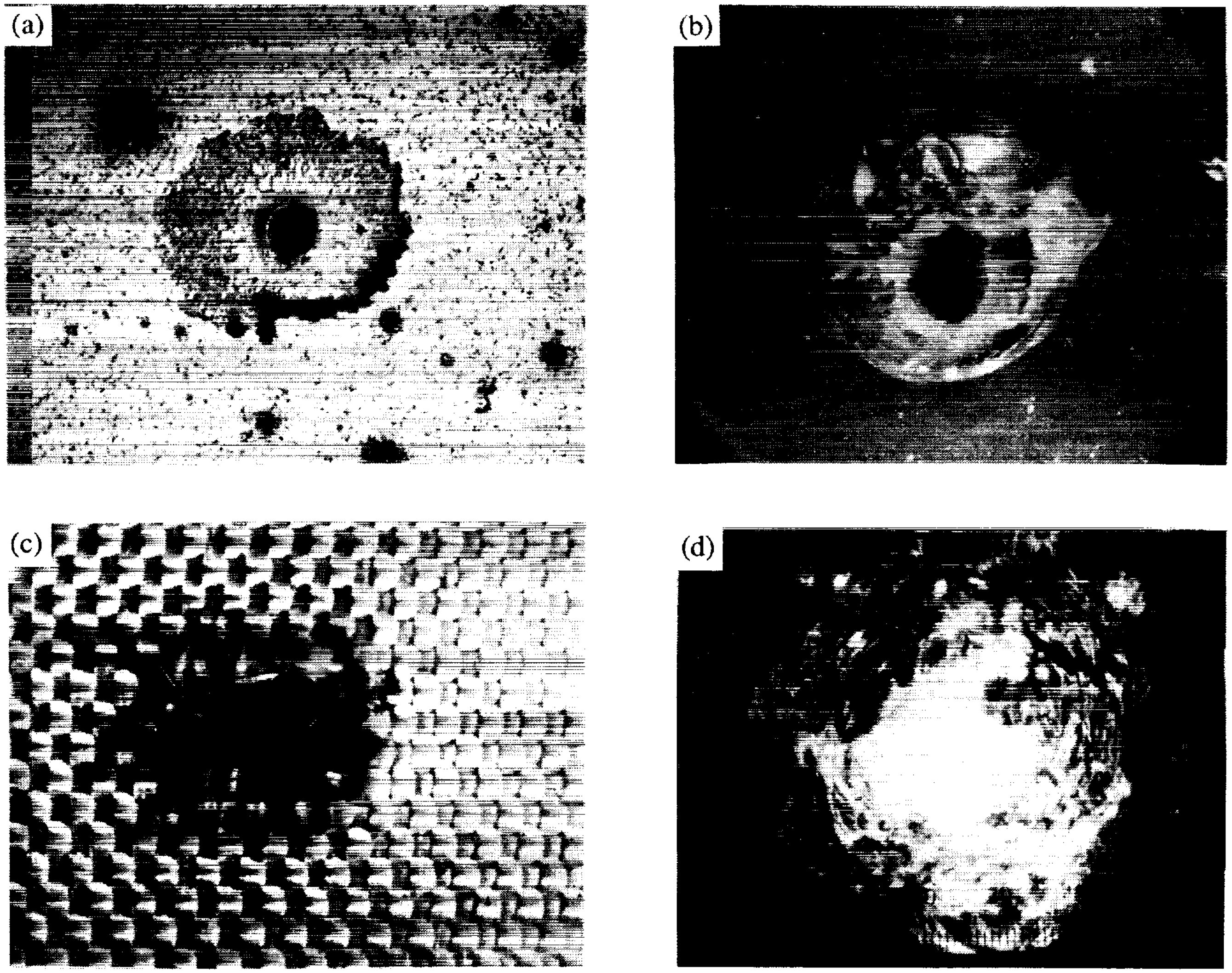


Figure 9. Impact phenomena generated in the hypervelocity facility typical of that seen on similar materials from LDEF. Photographs reproduced courtesy of J. Zweiner of the Marshall Space Flight Center.

The photo labeled 1 is an overall view of the impact site, which is some three hundred microns wide and five hundred microns in length. The x-ray scan below the crater image is typical of the area immediately adjacent to the crater. Note that the scan shows nothing but the copper of the specimen plate. The photo marked 2 is a high magnification image of the bottom of the crater. Immediately beneath it is the x-ray data which again shows no magnesium or gun contaminants within the sensitivity of our instrument. It appears that the site is at high temperature long enough to boil off any contaminants which might have come through the hole in the ballistic film routinely used in all of our experiments. Many sites within the crater were examined with the same result. Figure 11 is a closer analysis of the edges of the crater. All along the rim of the crater there are traces of the gun contaminants and the all important element, magnesium, which is indicative of olivine residue.

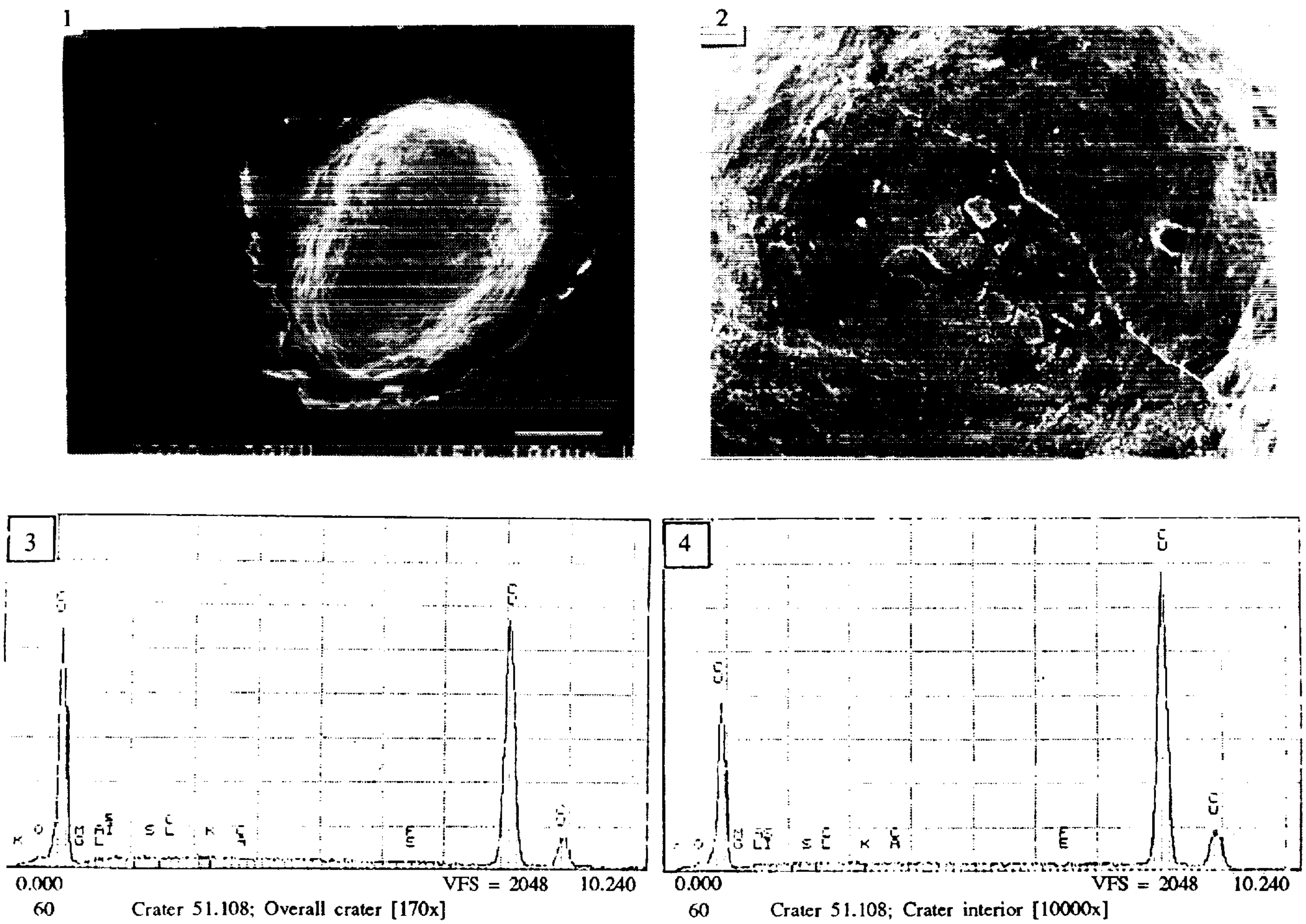


Figure 10. X- ray analysis of the residue external and internal to the impact crater for a velocity of 8.9 km/s. The impacting particle is olivine (magnesium iron silicate).

This same result has been obtained on other craters and is the subject of further research. To find ejecta from the crater containing material from the impacting particle on the rim of the crater is not inconsistent with the models for hypervelocity impact. A series of experiments are planned which will utilize the spheroidized olivine to produce many impacts over the range of 3 - 12 km/s. Selected craters will be examined for residual material, identifiable as being from the olivine, over the entire velocity range and as a function of location within the crater. The results of these experiments should clearly define the transition region where the result of impact is more akin to an explosion than to a penetration event where the materials remain largely intact and exhibit large plastic deformation rather than explosive vaporization.

Due to the large numbers of particles which can be accelerated simultaneously, the facility is useful to study accelerated aging phenomena associated with hypervelocity impact. In the 100 - 400 micron particle sizes, a single experiment is equivalent to many years in space. Figure 12 shows the impact distribution on solar cells produced from nominal 400 micron Al_2O_3 particles. A close-up of the individual craters is typical of that shown earlier on glassy materials. The maximum velocity for these particles is on the order of 8.5 km/s with the peak of the distribution on the order of 7 km/s. There have not been sufficient particles analyzed to accurately determine the velocity distribution.

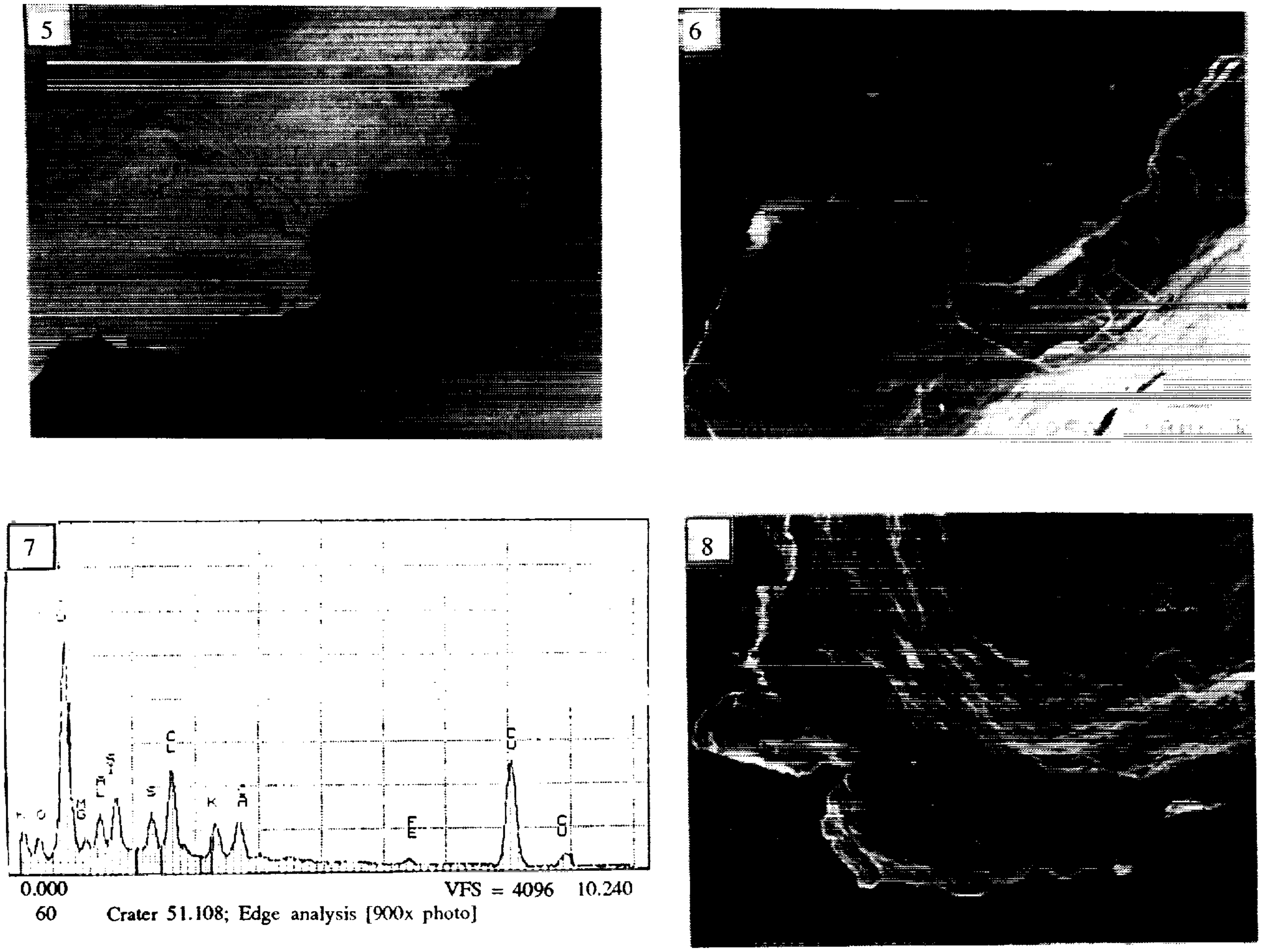


Figure 11. Electron micrograph of residue particles on the edge/rim of the crater in figure 10. X-ray dispersive analysis identifies gun contaminants and magnesium which is characteristic of the olivines used in the experiment.

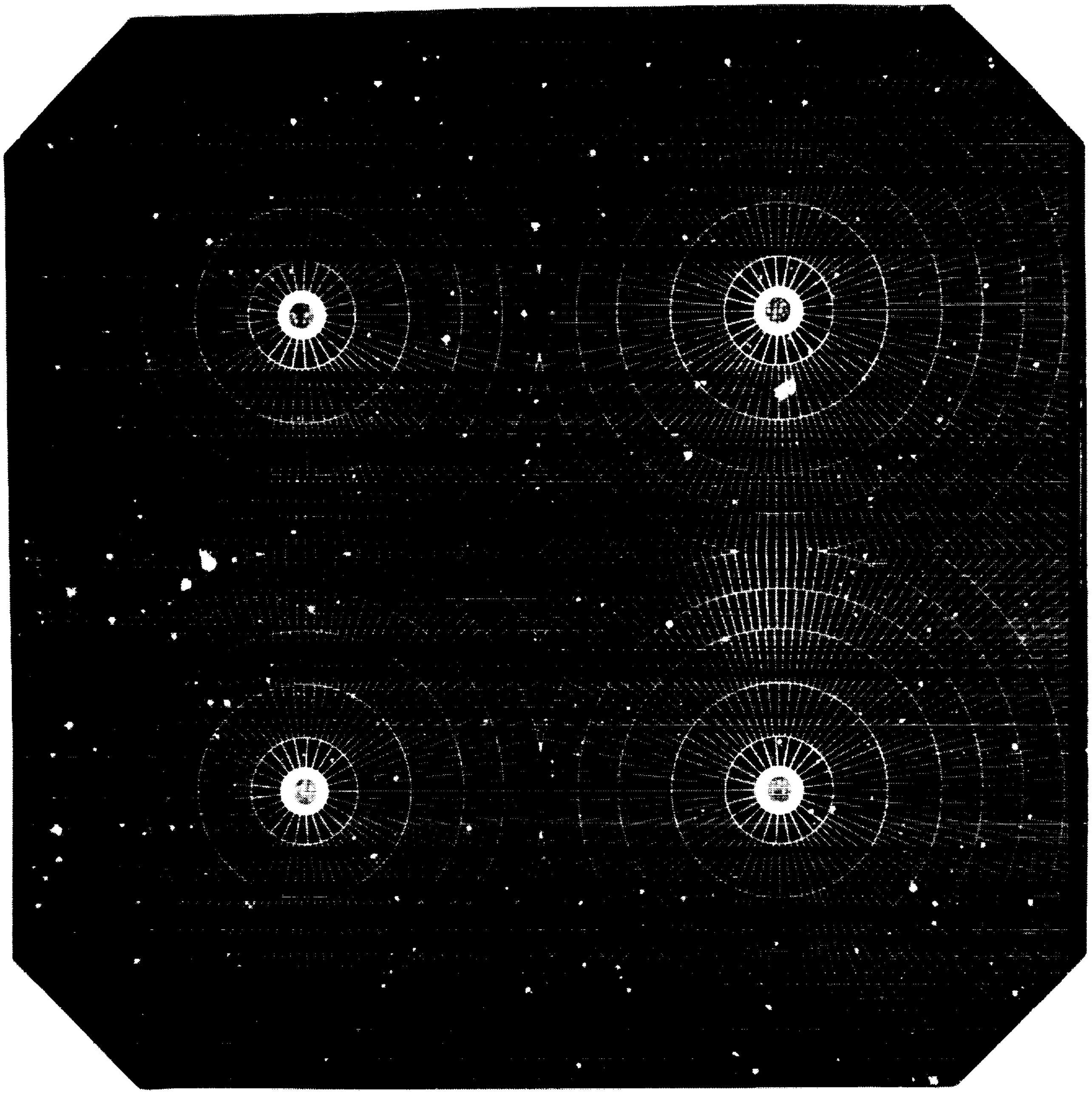


Figure 12. Impact distribution on solar cells typical of that planned for Space Station Freedom. Photograph reproduced with permission from R. Cristie of the Rocketdyne Division of Rockwell International.

SUMMARY

The hypervelocity impact facility located within the Space Power Institute at Auburn University is being used to study many phenomena associated with impacts on spacecraft and materials used in their construction. The facility has the following special attributes which make it unique and an outstanding tool to study impact and impact induced phenomena.

- Utilizes plasma drag phenomena to produce a particle stream with minimal breakup and a wide range of velocities in a single experiment.
- A wide range of materials can successfully be accelerated with the device.
- Capability to study accelerated aging effects by impacting target sample more than once without breaking vacuum.
- Advanced-unique diagnostic suite capable of tracking and completely characterizing up to 50 particles in a single experiment.
- Accelerator produced debris is minimal and identifiable resulting in a clean system.
- The facility is flexible enough to allow three experiments daily.
- The experiment chamber is large enough to accommodate large fully functioning spacecraft components or subsystems while under a variety of space stimuli such as ultraviolet radiation, micrometeoroids, space plasma, and atomic oxygen.
- There are up to 40 channels of electrical diagnostics available, some with bandwidth of 500 MHz.

ACKNOWLEDGEMENTS

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