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INTACT CAPTURE OF HYPERVELOCITY IMPACT PARTICLES AND EJECTA

C. R. Maag[1], W. G. Tanner[2†], T. J. Stevenson[3], J. Borg[4], J-P. Bibring[4],
W. M. Alexander[2] and A. J. Maag[5]

1. Science Applications International Corporation, Glendora, CA 91740 USA
2. Baylor University Space Science Laboratory, Waco, TX 76798 USA
3. ISST en Europe, Via XX Settembre 74, 10122 Torino, Italy
4. Institut d' Astrophysique Spatiale, 91405 Orsay Cedex, France
5. Stanford University, P.O. Box 11544, Stanford, CA 94309 USA

ABSTRACT

Many materials and techniques have been developed by the authors to sample the flux of particles in Low Earth Orbit (LEO). Through regular *in-situ* sampling of the flux in LEO the materials and techniques have produced data which compliment the data now being amassed by the Long Duration Exposure Facility (LDEF) research activities.

Several recent flight experiments have been conducted on the Space Shuttle (STS-32, STS-44, STS-46 and STS-52) as part of an ongoing program to develop an understanding of the spatial density as a function of size for particles 1×10^{-6} cm and larger. In addition to the enumeration of particle impacts, it was also the intent of these experiments that hypervelocity particles be captured and returned intact.

In addition to these Shuttle payloads, an experiment was developed and flown as part of the TICCE on the EuReCa 1 payload. This experiment has provided the opportunity to assess a wide range of dynamics of ejecta created by hypervelocity impacts on various substrates.

1. INTRODUCTION

Characterization of the space debris and micrometeoroid environment which any surface will encounter in LEO implies an implementation of several concurrent processes. Foremost, there should be a means to sample *in-situ* the flux with a frequency which can establish good statistics for multiple samples. There also should be access to that environment for an extended period, e.g., Solar Max, LDEF, so that the existence of any temporal fluctuations in that flux can be identified. The experiments flown can be passive sensors if the materials can be easily returned to Earth. In fact, a complete analysis of the LEO environment cannot be adequately conducted without repeated examinations of materials which have been exposed to space. Hence the experimental design which can provide a much needed investigation of small grains, $D_p \leq 10$ mm, would be passive sensors which could both detect and capture constituents of the space debris and micrometeoroid complex.

Unfortunately, the size distribution of objects a surface will encounter in LEO has not been adequately characterized; especially for that portion of the distribution which has the largest number of objects, i.e., micron and sub-micron sized grains. In order to provide *in-situ* data depicting the size distribution of the most populous objects in LEO, several experiments have been designed and flown aboard the Space Shuttle and a free-flying spacecraft.

2. EXPERIMENTAL DESIGN

A large body of experimental data exists concerning hypervelocity impacts. There are several empirical expressions relating the crater volume to the impacting particle size and mass and many previously flown experiments have examined these relationships. It is also well established that a part of the projectile mass is deposited and detectable on the inner surface of the impact crater. Despite being totally disassociated, elements detected from these sites allow course categorization of the impacting particle type, particularly with regard to all the important discrimination of space debris.

High purity metallic surfaces have been used for the collection of all grains down to submicron sizes (Ref. 1). During the impact, a characteristic crater is formed, with rounded habits and a depth to diameter ratio equivalent to the velocity and size of the impacting particle and the encountered metal. During the impact, the particle is destroyed and the remnants are mixed with the target material, concentrating in the bottom of the crater and on the surrounding rims. A major strength of the metallic collectors lies in the fact that analytical techniques can be applied without modification to the craters. Also, identification of carbon and organic material is quite possible; this is essential for the study of extraterrestrial material (C, H, O, N).

The impact of a hypervelocity projectile (> 3km/s) is a process which subjects both the impactor and the impacted material to a large transient pressure distribution. The resultant stresses, cause a large degree of fragmentation, melting, vaporization and ionization (for normal densities). The pressure regime magnitude, however, is directly related to the density relationship between the projectile and target materials. As a consequence, a high density impactor on a low density target will experience the lowest level of damage.

Historically, there have been three different approaches toward achieving the lowest possible target density. The first employs a projectile impinging on a foil or film of moderate density but whose thickness is much less than the particle diameter. This results in the particle experiencing a pressure transient with both a short duration and a greatly reduced destructive effect. A succession of these films, spaced to allow nondestructive energy dissipation between impacts, will reduce the impactor's kinetic energy without allowing its internal energy to rise to the point where destruction of the projectile mass will occur. An added advantage to this method is that it yields the possibility of regions within the captured particle where a minimum of thermal modification has taken place.

Polymer foams have been employed as the primary method of capturing particles with minimum degradation (Ref. 2). The manufacture of extremely low bulk density materials is usually achieved by the introduction of voids into the material base. It must be noted, however, that a foam structure only has a true bulk density of the mixture at sizes much larger than the cell size, since for impact processes this is of paramount

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† Currently at the University of Kent at Canterbury, Unit for Space Sciences, Kent CT2 7NR, United Kingdom.

importance. The scale at which the bulk density must still be close to that of the mixture is approximately equal to the impactor. When this density criterion is met, shock pressures during impact are minimized, which in turn maximizes the probability of survival for the impacting particle.

In addition to micro-pore foams, Aerogel has been used as the capture medium. Aerogel is particularly useful where extremely small cell sizes (~150 Å) are necessary. This material, in its silicon form, is commonly produced for the nuclear industry as a Cherenkov radiator, and has in fact been used in both space and balloon instrumentation. In comparison with polymer foams however, the extremely low densities (ρ = 0.035) cannot be achieved in any Aerogel without producing great fragility.

3. SHUTTLE EXPERIMENTATION

In an effort to develop such a system of sensors, the authors have designed and tested several prototypes on many STS missions. The primary means to test these devices has been on the Interim Operational Contamination Monitor (IOCM) developed under the auspices of the United States Air Force/Space and Missile Systems Center. The IOCM contains an array of passive and active sensors which continuously sample three orthogonal directions in the Shuttle cargo bay (Fig. 1). The IOCM has successfully flown on four (4) shuttle missions, the two (2) most recent being STS-32 and STS-44.

Although the primary objective of the IOCM on STS-32 and STS-44 was to verify the effects of the space environment to the cargo element, a secondary objective was to sample the LEO space debris and micrometeoroid complex using an array of passive sensor experiments. An additional design goal for these experiments was to test the survivability of thin film sensors with a thickness of less than 750 Å.

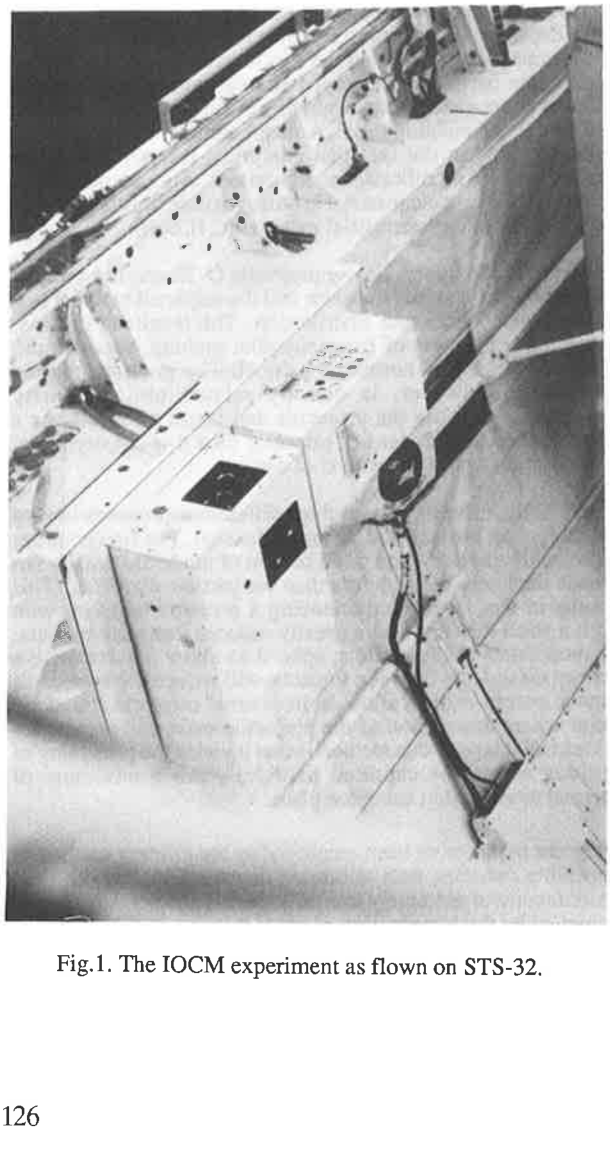

Fig.1. The IOCM experiment as flown on STS-32.

The Limited Duration Space Environment Candidate Materials Exposure (LDCE) experiment was launched on STS-46. LDCE-1 and -2 were mounted in GAS canisters with door assemblies. LDCE-3 was mounted on the top of the Space Complex Autonomous Payload (CONCAP). Figures x and y depict the layout of the LDCE-1 and -2 exposure plates after integration into the GAS canisters. The GAS canisters were located in Bay 13 of OV-104. The samples mounted on LDCE-3 were exposed for the entire duration of the mission. After the door assemblies of GAS canisters open, the samples mounted in the LDCE-1 and -2 were exposed for a period of forty (40) hours. The exposure occurred towards the end of the mission, near 200 km, with a continuous payload bay attitude into the velocity vector. The LDCE experiment flew principally to understand the influence of Atomic Oxygen on materials. Our array of senors were uniquely designed for the detection of hypervelocity impacts (HVI).

The LDCE-1 and -3 HVI sensors were exact duplicates except for a polished graphite specimen onto which a Niobium grid was deposited. This sample was used to deduce the LDCE-3 mission atomic oxygen fluence. The LDCE-1 HVI package contained a gold foil (nominal T_f ~4.0 µm) that covered a low density micropore foam. Similar foams had been used on past missions to collect hypervelocity particles, intact. A similar piece of gold foil covered a highly polished aluminum strip coated with vacuum deposited gold. This aided in the understanding of the distribution of ejecta material. Also included was a thin aluminum film (nominal T_f < 500 Å) stacked above a coated substrate. It was hoped that an estimate of the trajectory of grains within the experiment could be derived from the analysis of penetrations made in the thin film and impact sights (these data have not yet been reduced). The last group of passive sensors were high purity metallic surfaces used for the collection of grains down to sub-micron size.

The LDCE-2 HVI package contained materials and sensors useful in understanding the effects of both atomic oxygen and hypervelocity impacts on the optical properties of engineering materials. Two (2) low scatter mirror specimens, a Kapton™ material sample and an aluminum film (nominal t_f < 500 Å) were used. The LDCE-1 and -2 aluminum films, with a total surface area of 3.24 X 10^{-4} cm^2, should have experienced 5.2 particle impacts in ten days while in LEO. This estimate was based on Pegasus data published in 1970. Using a foil thickness of 7.24 X 10^{-5} cm, a density of 2.8 g/cm^3, and a velocity of 7 km/s, the minimum mass which could penetrate the thin film was calculated. The thin films could be penetrated by a grain which possesses a mass greater than a picogram.

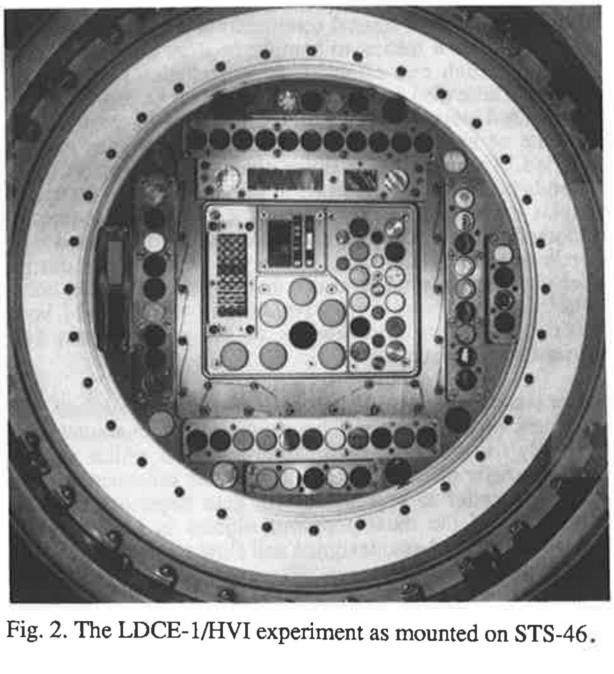

Fig. 2. The LDCE-1/HVI experiment as mounted on STS-46.

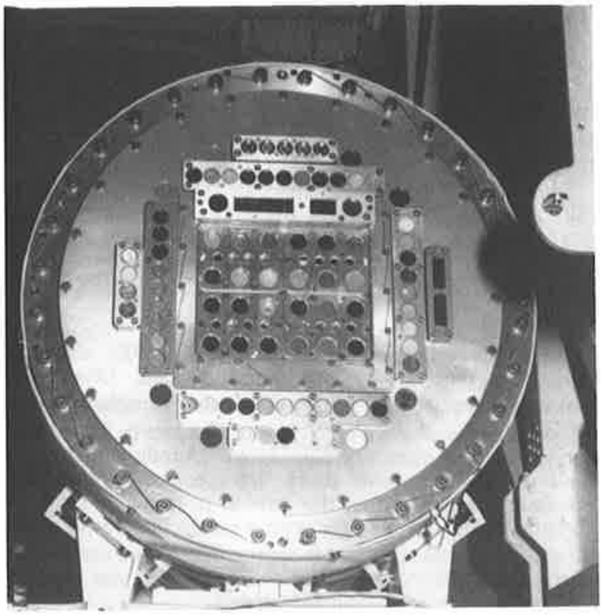

Fig. 3. The LDCE-2/HVI experiment as mounted on STS-46.

4. EURECA EXPERIMENTATION

As a consequence of the experimental data developed during both recent and earlier STS missions and the data expected from this mission, the authors have produced and delivered an experiment for the European Space Agency, European Retrievable Carrier (EuReCa 1). The HVI experiment was flown as part of the TICCE experiment (Fig. 4). The EuReCa payload was launched on OV-104 (Atlantis) on 31 July 1992. The payload was deployed approximately 30 hours later. This experiment has provided an opportunity to assess a wide range of dynamics of ejecta created by hypervelocity impacts on various substrates. EuReCa 1 will provide a nine-month exposure at 500 km.

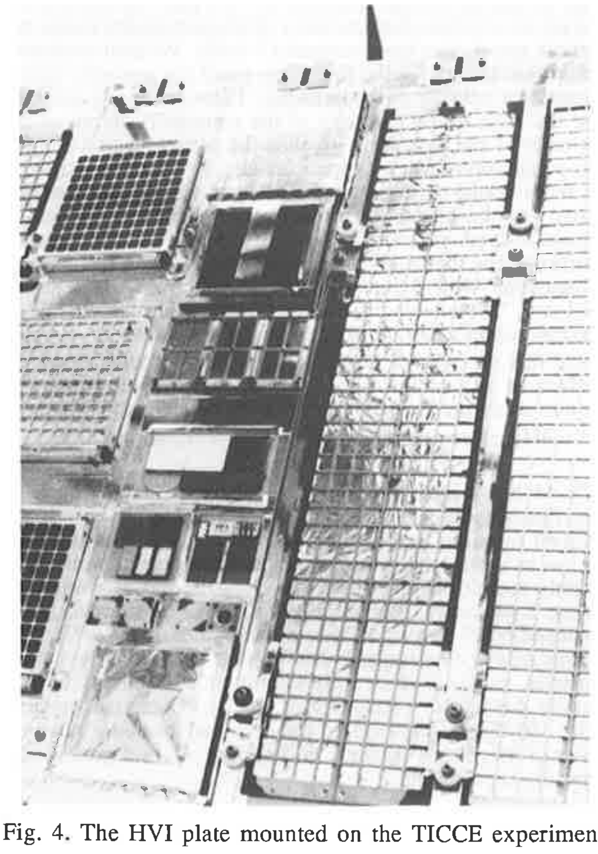

Fig. 4. The HVI plate mounted on the TICCE experiment.

Few HVI experiments (flight or laboratory) have investigated the mechanisms of ejecta creation. Experimental data suggest that oblique hypervelocity impacts create more ejecta particles than normal incidence impacts. Research has also shown that craters caused by ejecta from an impact will be greatest for a few discrete angles, viz., 17°, 45°, 81° (Ref. 3). Experimental and theoretical analyses also suggest that the ejecta particle size and velocity distribution are apparently strong functions of ejecta elevation angle. Hence, small high-speed ejecta particles dominate the distribution at small angles with respect to the impact surface, while larger, slower ejecta particles dominate the distribution at large angles with respect to the impact surface. For these reasons our experiment was designed to reveal the angular dependency of ejecta particles.

4.1. Objectives of the TICCE/HVI Experiment

The primary objectives of the experiment are to: (1) Examine the morphology of primary and secondary hypervelocity impact craters. Primary attention will be paid to craters caused by ejecta during hypervelocity impacts on different substrates, e.g., gold, aluminum, carbon, and at different angles of incidence, viz., 45°, 30°, 15°, 0°; (2) Determine the size distribution of ejecta by means of witness plates and collect fragments of ejecta from craters by means of momentum sensitive micro-pore foam. With an established ejecta size distribution via witness plates, and with the determination of total momenta of each ejected particle, a velocity distribution by angle will be derived; (3) Assess the directionality of the flux by means of penetration hole alignment of thin films placed above the cells. Theoretical work using Sandia Laboratory's CTH "hydro" code (Ref. 4) has been performed to assess the lower bound on the mass which could cause a penetration hole of the 1000Å of aluminum thin film; (4) Attempt to capture, intact, the particles which perforated the thin film and entered the cell. Capture medium consists of both previously flight tested micro-pore foams and Aerogel. The foams have a different latent heat of fusion and accordingly, will capture particles over a range of momenta (fig. 5). Aerogel has been incorporated into the cells to determine the minimum diameter that can be captured intact.

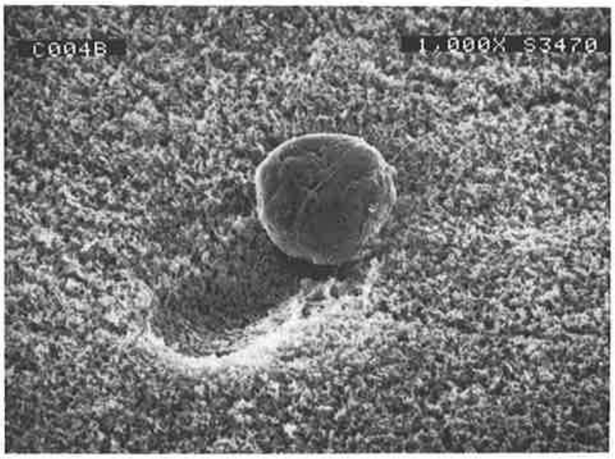

Fig. 5. Aluminum oxide sphere, 8 μm diameter, recovered from foam. The encrusted pyrolyzed foam is easily removed, leaving an undegraded specimen.

In addition to these principal objectives, the EuReCa experiment also provides a structure for the exposure of passive material samples to the space environment, e.g., thermal cycling, and atomic oxygen, etc. Experience on Shuttle flights has shown that atmospheric interactions with surfaces in LEO can have significant effects on the performance of materials. At altitudes of 200 to 700 km the predominant species is atomic oxygen (AO) and at altitudes above this, it remains a significant constituent. The atomic oxygen density in LEO is not particularly high even at shuttle altitudes; the 10^{-9} atoms/cm^3 corresponds to the density of residual gas in a vacuum of

10^{-7} torr. However, due to the high orbital velocity (approx 8 km/sec at Shuttle altitude), the flux is high indeed; being of the order of 10^{15} atoms/cm^2-sec. The effect of the bombardment has been confirmed through past Shuttle flights on materials such as Kapton™, graphite-epoxy composites, paints and some metals such as silver that have experienced surface erosion and mass loss after only hours in LEO. A few samples for AO erosion studies were included onto the TICCE/HVI experiment.

The EuReCa 1 payload is scheduled for retrieval on STS-57 (10 May 1993 launch).

4.2. Data Analysis and Expected Results

During the decades ahead, a significant amount of material which, will be, or has been exposed to the LEO environment will be returned for analysis. Interpretation of the evidence presented by these materials will require extensive knowledge concerning the failure modes of similar materials subjected to hypervelocity impacts. An accurate assessment of the properties of objects which might have created the features evident on the returned materials will insure that an exact "picture" of the space debris and micrometeoroid population can be developed. To this end, experimental investigations have measured the penetration parameters of several types of metallic substances in the velocity and size regimes commensurate with that of Interplanetary Dust Particles and space debris. Through hypervelocity impact investigations, other researchers have accumulated experience which has been applied to the utilization of the multi-dimensional hydrodynamics code, CTH (Ref. 5) produced by Sandia National Laboratory. Primarily, CTH will be used to investigate the relationship between the particle diameter, d_p, and the diameter, d_h, of the hole created in the aluminum thin films [500 Å thick (T_f)] for relevant particle sizes, densities and velocities. The results of these CTH runs will be employed to analyze the penetration parameters of the thin films flown on EuReCa 1. Equations which have been derived by empirical means will be utilized to assess the "fit" of the hydrodynamic computer program CTH at the low velocity-high density regime.

4.2.1. Data Analysis

Primary analyses will be performed using a Scanning Electron Microscope (SEM) outfitted with a Princeton Gamma Tech (PGT) elemental analysis system (Beryllium window). Since each unit cell will be ~10 mm square, samples will be easily prepared for viewing in the SEM. The SEM is sufficiently large to support the viewing of 5 cm substrate material.

Count of hypervelocity impact craters on the witness plates whose diameters are larger than 4 µm will be accomplished by the use of SEM photographs. Once digitized by means of a high-resolution optical scanner, these data will be analyzed using a hypervelocity impact morphology system.

Analysis of the substrate will be of particular importance. The same procedure outlined above to analyze the witness plates will be applied to the substrate. Of primary interest will be the recovery of data concerning the affects on the substrate's surface attributes, e.g., reflectivity, refractivity, albedo, etc., which have been subjected to primary and secondary hypervelocity impacts. Also recoverable from the substrate (and perhaps the witness plates) will be data pertaining to the fragmentation of grains by the thin films.

Principal theoretical analyses will be conducted using the "hydro" code CTH to establish the limiting mass which will penetrate all, two, or only one of the thin films. Comparisons of the computational results with experimentally derived parameters will be carried out.

4.2.2. Expected Results

Based on the present knowledge of the space debris and micrometeoroid fluxes, all cells should be penetrated by grains with the properties:

$m_p = 3.4 \times 10^{-13}$ g; $\rho_p = 3.8$ g/cm^3; $v_p = 7.00$ km/s; thus, $r_p = 0.3$ µm.

Given that we expect EuReCa to be in orbit for approximately one year, then there should be ~50,000 impacts/m^2; with 100 cm^2 (1.0×10^{-2} m^2), the HVI experiment should expect 3.75 impacts/cell from grains which are this size and larger. In addition to the 200 unit cells, the HVI contains high purity metallic surfaces plus 200 cm^2 of micro-pore foam.

5. SUMMARY

The experimentation on the shuttle (1983-1992), although snapshots in time, has yielded interesting data. One of the more salient results suggest that the smaller particles, 10^{-4} to 10^{-2} cm diameter, have a much higher flux rate (~ 2 orders of magnitude) than currently considered. Another interesting result of the long-term study, irrespective of the high uncertainty, suggests that the growth in this size range is approximately six percent per year; whereas, the growth of the 10^{-2} to 10^{-1} cm diameter size is approximately two percent per year. LDEF, unfortunately, due to its extended stay on orbit could not provide population growth data.

The program also developed/modified a family of materials useful in intact capture particle studies. A reasonable number of particles (250) have been captured intact using micropore polymeric foams. Three (3) bonafide IDPs were captured and returned intact.

5.1. Summary of Results from Recent Shuttle Flights

The passive space debris/micrometeoroid sensors suggest a flux of 0.2×10^2 impacts/m^2 occurred during the STS-32 mission (7 day duration). The average diameter of the perforations was ~12.5 µm. The largest perforation measured was 65 µm.

Several impact sites on the films were detected by use of an SEM and photographic equipment. One perforation of interest (Fig. 6) had an average diameter of ~5.5 µm. Given that the impact site exhibits characteristics of a hypervelocity event, the particle speed must have exceeded 7 km/s. Without extensive calibration studies for the films, one could not precisely assess the mass or velocity of the impactor. However, if one assumes that the ratio of the diameter of the crater/perforation to the diameter of the particle is ~2, then the particle which created this penetration must be approximately 2 - 3 µm in diameter. Its mass could be about a picogram if we assume that the density of the particle is close to that of Silicon Oxide. A second impact of interest can be seen at the "5 o'clock" position. The diameter of this perforation is ~0.3 µm. These dimensions would imply an impacting grain diameter of ~0.1 µm. There were many very small impacts which will be reported upon when more data can be analyzed. It was also noted that the erosive nature of O^+ did not greatly affect the surface of any of the films. Of course, thinner films will require more precise analysis upon return since the effects of O^+ will be more pronounced after the same exposure time.

STS-44 has proved to be one of the most interesting HVI experiments placed on the Shuttle. During the course of the STS-44 mission, the Space Shuttle corrected its altitude by 26 km to evade a spent upper stage. The object, which was slightly outside the given collision ellipsoid, was determined to be the Kosmos 851 rocket body (Ref. 6). Kosmos 851 was launched on 27 August 1976 into an 81° inclination orbit. The results of our data suggest that a cloud of irregularly shaped particles, most of which were aluminum oxide, impacted the Shuttle during the mission (Figs. 7 - 9). Data also suggests (Fig. 10) that the associated debris cloud caused a nearly 2 order of magnitude increase in flux over the background flux typically experienced.

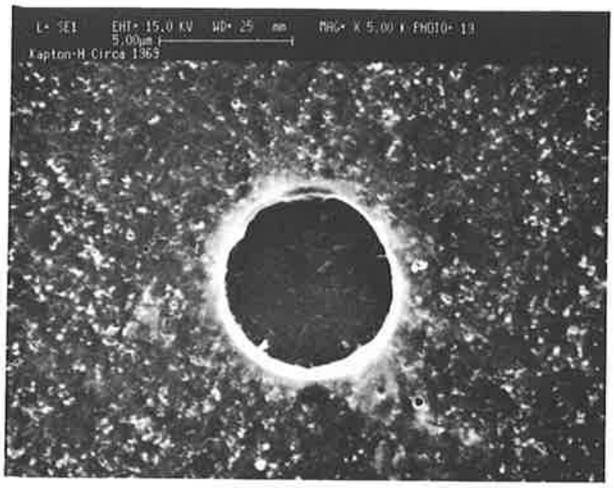

Fig. 6. Film perforations occurring during STS-32 flight.

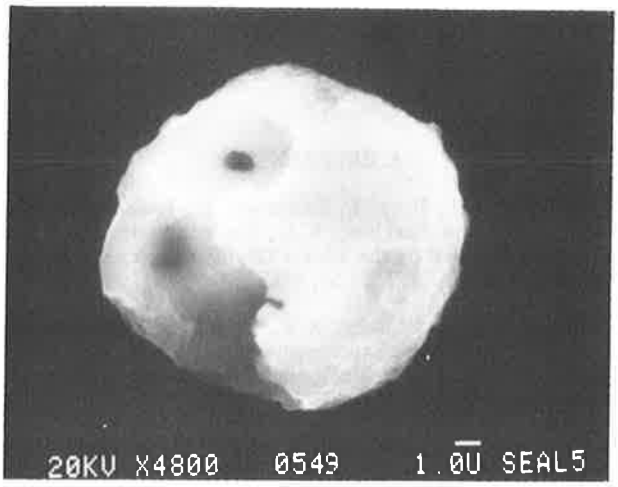

Fig. 7. Irregularly shaped Al_2O_3 captured particle (STS-44).

Other major impacts on STS-44 were primarily due to low-velocity, low-density substances. Investigation of these sites, revealed no hypervelocity impact features and only small evidence of residual materials left by the impactor (Fig. 12). Shallow and wide impressions in the films were seen immediately adjacent to the perforation sites. The morphology of these sites suggests that low-density material formed the impressions. On the impact plate beneath the suspended thin film no evidence of hypervelocity impacts were seen. Continued investigations of the substrate surface at higher magnification will be reported on at a later date. The material discovered on the impact or substrate plate has been tentatively identified as pieces of the ruptured film which came to rest after being removed from the thin film above. Consequently, the information derived from these "perforations" can lead one to conclude that a considerable number of low-density impacts occurred during the seven-day LEO exposure on STS-44. It is thought that the impacts come from water ice dumped by the Shuttle. Water and waste dumping from the Orbiter can create significant amounts of gaseous and particle contaminants (Fig. 13). These materials and the propulsion contaminant mass remain near the Orbiter for some time before they disperse.

Very preliminary data from STS-46 suggests that nine impacts and perforations occurred during the course of the mission. One of the particles captured intact has tentatively been identified as an IDP.

5.2. Summary of Results from EuReCa Studies

Data from the two-dimensional (2D) computer simulations of hypervelocity impact events for the TICCE/HVI thin films conform to a high degree with the Carey, McDonnell, and Dixon (CMD) equation (Ref. 7), for all densities tested. The CMD relationship will be compared with experimentally derived penetration data to be collected this year, as well as with further CTH computer simulations at higher velocities, i.e., 9, 11, and 15 km/s. These computer simulations suggest that the CMD relationship may be used to analyze the thin film experiments flown on both the LDCE and EuReCa, and to determine the size distribution of particles which penetrate the thin films.

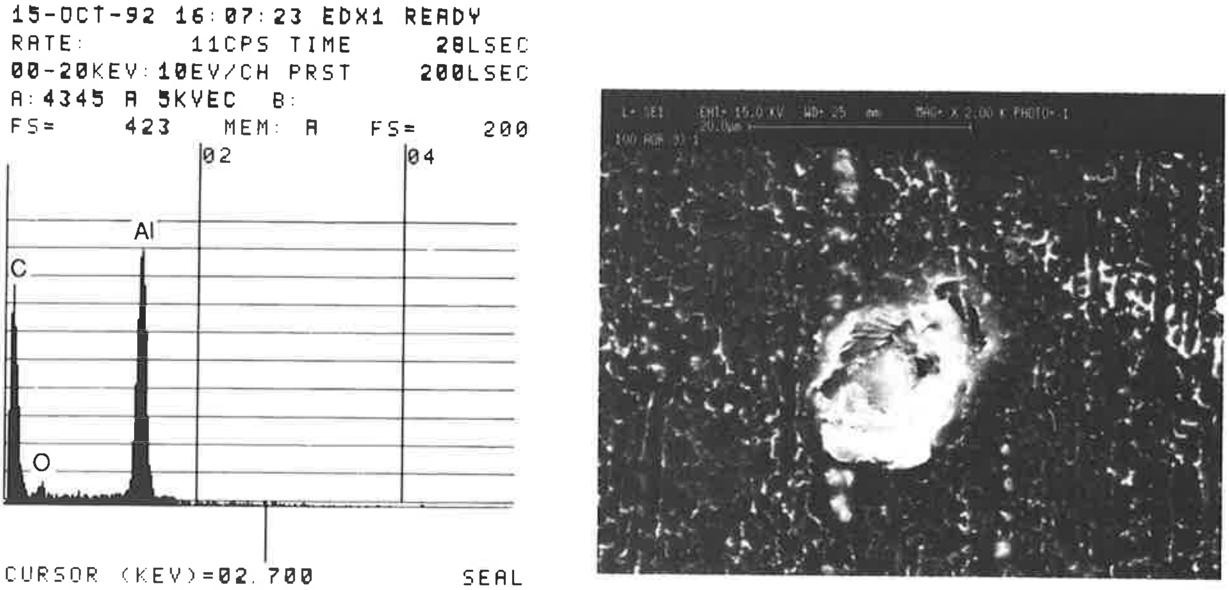

Fig. 8. Intact captured Al_2O_3 particle with EDS spectra (STS-44).

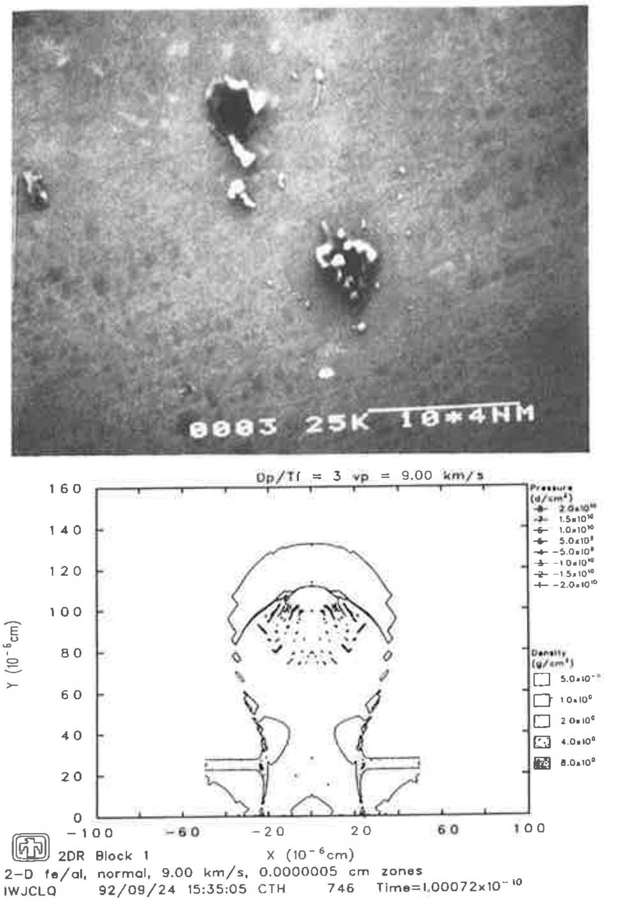

Fig. 9. Inverse of Au film showing two impacts with ejecta spray. Modelling using the multi-dimensional hydrodynamic code, CTH, shows similar phenomena.

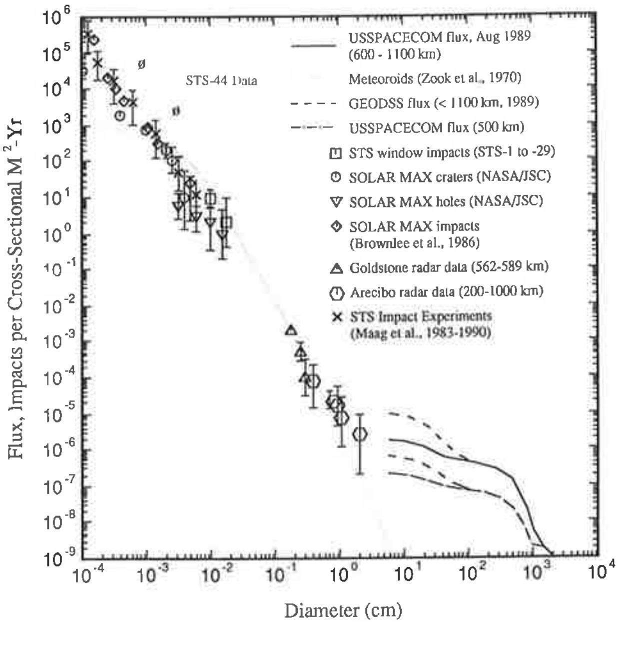

Fig. 10. Flux curve showing STS-44 impact data (significant departure from nominal).

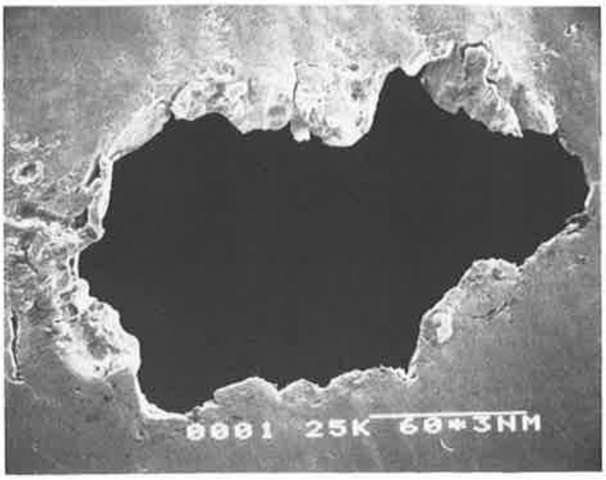

Fig. 11. Perforation and tearing of Au film from apparent low velocity impact. Residue can be seen around periphery.

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