Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

MEASUREMENT AND COLLECTION OF SPACE DEBRIS AND METEOROIDS USING THIN FILMS AND MICROPORE FOAMS

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ABSTRACT

Thin film experiments flown on the U. S. Space Shuttle (STS) have produced data which substantiate theoretical calculations describing the penetration dynamics associated with hypervelocity thin film perforations. A ten-month measurement of the Space Debris and Meteoroid population is being made by an experiment on-board the EuReCa 1 spacecraft and will be returned for examination in May 1993. The ten-month exposure of the thin film experiments to Low-Earth Orbit (LEO) will produce data which will allow further characterization of the Space Debris and Meteoroid population as well as the effects that population has on materials. Results from the data analysis will provide verfication for an augmented sensor system which will be included in a space environment package named COMRADE, described elsewhere in these proceedings (Ref. 1).

1. INTRODUCTION

The authors have been primarily interested in the determination of the population of micrometeoroids and space debris and have sought to interpret the hole size in a thin film or in a micropore foam returned from space with theoretical calculations describing the event. In order to augment the significance of the theoretical calculations of the impact event, an experiment designed to analyze the charge production due to hypervelocity impacts on thin films also produced data which described the penetration properties of micron and sub-micron sized projectiles. The thin film penetration sites in the 500Å and 1000Å aluminum films were counted and a size distribution function was derived. In the case of the very smallest dust grains, there were no independent measurements of velocities like that which existed for the larger dust grains ($d_p \geq 1$ μm).

The primary task then became to assess the relationship between the penetration hole and the particle diameter of the projectile which made the hole. The most promising means to assess the measure of the diameters of impacting grains came in the form of comparing cratering mechanics to penetration mechanics. Future experimentation will produce measurements of the cratering as opposed to the penetrating event. In addition, hypervelocity penetrations of a 250Å and 500Å aluminum thin film were characterized by a charge liberation event ($v_p \geq 3$km/s). These data provide further evidence needed to establish the size of the projectiles which made the perforations in the thin films. Surfaces which encounter particles while being flown in space will degrade in a systematic manner even when the impact is with small hypervelocity particles, $d_p < 10$ μm. Though not to a degree which would precipitate a catastrophic failure of a system, degradation of the materials comprising the interconnected systems will occur. The lose of resolution of an optical system or the subsequent embrittlement of other materials can lead to degradation if not to failure. It is to this end that research has been conducted to compare the primary consequences for experiments which will be flown to those which have been returned.

Systems exposed to the extreme environment of LEO can avoid catastrophic failures only if the materials which compose them can provide a "shield" against the effects of continuous hypervelocity impacts. To obtain *in situ* data depicting the size distribution of these objects in LEO, several experiments have been designed and successfully flown in the Science Applications International Corporation (SAIC) Interim Operational Contamination Monitor (IOCM) aboard the STS-32, STS-44, and the Particle Impact Experiment (PIE) aboard STS-46 and STS-52 . Each of these shuttle secondary experiments have been scheduled for flight on STS-53 (PIE) and STS-63 (IOCM). As a result of experimental activities associated with Carl Maag's IOCM and PIE payloads, an opportunity to participate in the ESA's European Retrievable Carrier (EuReCa 1) was provided for a ten-month exposure at 525 km for similar thin film experiments.

2. EXPERIMENT DESCRIPTION

The small-size Space Debris and Meteoroid population has received little attention, and few experiments have been devoted to the measurement of these abundant dust grains. In order to supply data for both theoretical and experimental research, the EuReCa / TiCCE experiment includes an intact capture system which will non-destructively decelerate small Space Debris and Meteoroid grains. The detection and collection of Space Debris and Meteoroids will improve knowledge concerning the size distribution of the cosmic dust grain complex and will provide parameters for larger body break-up models.

A primary objective of the EuReCa / TiCCE thin film experiment has been the identification of materials which could withstand the harsh LEO environment and be only moderately destructive to dust grains of unknown density ($D_p \geq 10$μm and $\rho_p < 1$g/cm^3) which would penetrate. In response, researchers constructed means to assess the minimum mass capable of penetrating thin film thicknesses. Of equal importance was the assessment of the viability of trapping particulates below a film given that fragments of the original grain could be widely dispersed or destroyed through vaporization. It should also be noted that the velocity regime, v_p ~7km/s, can be assumed to be constant for the most abundant portion of the dust grain size distribution, i.e., Space Debris. However those with much greater velocity could not be collected without severe alteration of a majority of the grain's mass. That conclusion presupposes that destructive capture of grains will be the only possible fate for Interplanetary Dust Particles (IDPs) while Space Debris could be captured intact and thus perserved for analysis.

The main theoretical thrust of research remained to establish a relationship for the 500Å films now being flown on EuReCa/TiCCE. Together with calculations produced by a hydrodynamic computer program (Sandia National Laboratory's CTH) and experiment data generated by use of an electrostatic dust accelerator (University of Kent at Canterbury, UK), a hole size relationship for hypervelocity thin film penetration can be developed which will aid in the interpretation of the data returned by the EuReCa/TiCCE experiments. The results of the calibrations can then be used to assess the size of grains which perforated the 500Å film and were decelerated in the micropore foam. Preliminary analysis concerning theoretical limits for intact capture of Space Debris and Meteoroids in micropore foam can also be compared with previous laboratory studies of foam penetration.

2.1. EuReCa 1 Experimental Design

Each 100 mm x 100 mm x 8 mm unit possesses an ultra-thin aluminum film (nominal $T_f < 500$ Å) stacked above a coated substrate (Fig. 1.). The plane of each film contains 100 cm^2 of impact surface under which a Buckbee Mears (90% transmissive) grid is placed to support the ultra-thin film. Each mesh has been covered with an aluminum-coated epoxy layer nominally 5 µm thick to inhibit production of X-rays by 20keV electrons during laboratory analyses. An estimate of the trajectory of grains within the experiment can be derived from analysis of penetrations made in the thin film and impact sights. Beneath the thin film and above the substrate a network of collimating plates have been constructed. Each highly polished 0.625 mm thick 3300 aluminum plate is 100 mm long with a height of 8 mm, and possesses slots so that it can interlock with perpendicular plates. These divisions insure that grains whose velocity vectors make a large angle with respect to the surface normal of the 500 Å film will not impinge on another cell but will impact the witness plates of a specific cell or be stopped by a thin film. The 3300 aluminum witness plates will also record the demise of "barely" penetrating grains.

The underside of each thin film will be investigated to assess the constituents of debris clouds deposited on each thin film. The primary function of the 3300 aluminum witness plates near the substrate will be to record the ejecta produced when a hypervelocity grain encounters a semi-infinite stopping plate, viz., the substrate, which has been coated with 2000 Å of gold. Each portion of the substrate surface need not be normal to the particle's incident direction. In fact, since the grains which penetrate the film will be directional, the effects of oblique hypervelocity impacts can be examined using the orbital debris and micrometeoroid complex. A maxmium angle of 45° with respect to the substrate surface normal has been accommodated in the design of several of the

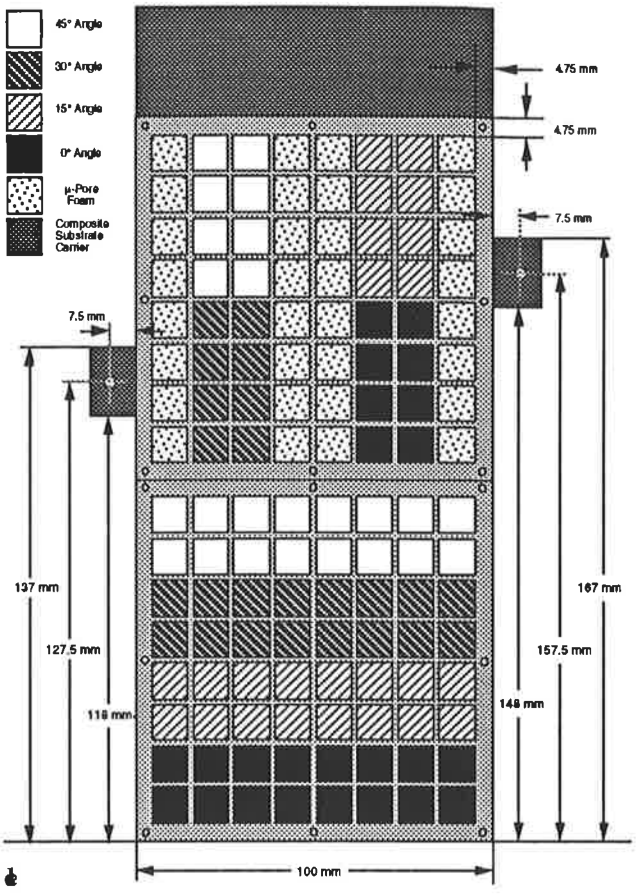

Figure 1. EuReCa/TiCCE hypervelocity impact experiment

3. SCIENCE OBJECTIVES

Few laboratory hypervelocity impact experiments have investigated the mechanisms of ejecta creation. Consequently, a significant uncertainty attends predictions of the effects high-speed ejecta can have on surfaces lying near the site of a hypervelocity impact. For this reason, the effect on materials which will be incorporated into the design of future Earth-orbiting vehicles needs to be investigated by exposure to long-duration space flight conditions. The experiment described above will provide the data necessary to assess a wide range of dynamics of ejecta created by hypervelocity impacts on various substrates.

The existing experimental data suggest that an oblique angle hypervelocity impact can create much more ejecta particles than do normal incidence impacts, and that the velocity distribution of these ejecta particles will be skewed toward higher values. Therefore, ejecta created in oblique impacts will transfer a significant portion of the impactor's kinetic energy to the surrounding structures. In order to examine this phenomenon further, the authors saw a need for an experiment which could capture hypervelocity ejecta so that an ejecta size and velocity distribution might be derived from a non-destructive study. The effects which a variation in the density of the substrate might have on ejecta production is also being investigated. Eulerian and smooth particle hydrodynamic computer programs will assist in establishing the theoretical parameters for the full regime of impact events from ultra thin film penetrations to semi-infinite targets composed of mixed material systems, viz., metallic surface evaporated onto a substrate.

3.1. Objectives of the EuReCa/TiCCE experiment:

The experiment which will be exposed to LEO for ten-months will return data revealing much about hypervelocity impacts in space. The EuReCa/TiCCE experiment described above will:

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, palladium, copper, 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 [above each cell, a 500 Å aluminum thin film will be placed. Particles larger than 0.3 µm ($\rho_{Al2O3} \sim 3.8$ g/cm^3) and 2.0 µm ($\rho_{IDP} \sim 1.0$ g/cm^3) will penetrate 500 Å of film]. Theoretical work using Sandia Laboratory's CTH "hydro" code (Ref. 2) will be performed to assess the lower bound on the mass which could cause a penetration hole of the thousand angstroms of aluminum thin film;

4) Attempt to capture, intact, the particles which perforated the thin film and entered the cell. Capture medium will consist of both previously flight tested micro-pore foams and Aerogel. The foams have different latent heats of fusion and accordingly, will capture particles over a range of momenta. Aerogel will be incorporated into the cells to determine the minimun diameter that can be captured intact. A complete description of all experiment designs, and data analysis techniques has been given in another paper in these proceedings (Ref. 3).

4. PENETRATION MECHANICS

Hydrodynamic computer programs have benefited greatly from the data provided by many experiments designed to assess the effects of high-shock conditions present in materials. Principally the "hydro-code" calculations possess equations of state which describe both the elastic-plastic and the phase transition with melt of the high-shock regime. For several years research has been underway to assess the association between specific thermodynamic properties of materials and the process of fragmentation, i.e., the catastrophic failure of materials.

The primary description of the event has evolved from the study of the very early stage creation of ejecta spray patterns liberated from the semi-infinite target via hypervelocity impact and the subsequent shock wave disruption of the target and projectile material. The formation of ejecta patterns seen in experimental work was utilized to test the validity of a hydrodynamic computer code designed to track the progress of a hypervelocity cratering event. Hypervelocity impact experiments have suggested a set of preferred angles, viz., 15°, 45°, 60°, 80°, at which the ejecta spray size distribution is spread by some as yet unexplained process. In practice most "hydro-codes" will reproduce results commensurate with those derived from normal and oblique semi-infinite target impacts.

Perhaps the most important results of these analyses will be tested, i.e., angles of incidence with surface controls size distribution of ejecta, by data collected via EuReCa/TiCCE now on orbit. Upon return in May 1993 materials exposed to ten months of LEO will yield data of oblique impacts with a specific capture material located near impact sites to capture ejecta particles for size and velocity distribution analysis.

Using CTH, many properties of hypervelocity particle thin film capture techniques have been theoretically analyzed. Hypervelocity perforation of thin films will fragment glass spheres which have been used to simulate Interplanetary Dust Particles (IDPs). Upon impacting a thin film with hypervelocity a small IDP analog will fragment if and only if the film thickness and the IDP analog's velocity are sufficient. Hence the coupled parameters of velocity and D_p/T_f ratio will determine the degree of fragmentation the thin film will cause in the IDP analog. With a hydro-code calculation one can investigate many different values for velocity and film thickness and the results of that work have been previously reported (Ref. 4). The fragmentation process arises from the activation of various fragmentation sites within the non-perfect crystal. The sites which are crystal defects can be stimulated into action by a shock wave's passage through the sites which will cleave the crystal along a defect boundary. A specific size defect has been found to activate at a specific shock velocity and thus can be stimulated to fragmentation by high or low velocity (2 - 10 km/s).

CTH has been used to investigate the penetration mechanics of small particles impacting and perforating a thin film. The fragmentation of IDP analogs have been investigated to determine penetration parameters of thin films. The same analysis can be applied to the fragmentation of targets or projectiles or even secondary impacts due to ejecta sprays.

Smooth Particle Hydrodynamics (SPH) and Molecular Dynamics (MD) computer programs can provide a means to establish the velocity distribution of the small particles which are created during a fragmentation event. Utilization of SPH and MD can provide a means to describe particle fragment motions. Fragmentation events can therefore be fully characterized using SPH and MD since particles will move under Newtonian kinematics and thus the equation of motions can be well defined. Clusters of particles can be employed in the interaction to develop macroscopic scaling rules.

4.1. Passage of particle through a thin film

The pressure an impacting dust grain experiences during a hypervelocity impact can be sufficient to alter the state of matter of the particle. However, very short duration high-pressure pulses can be sustained in large dust grains without pressure pulses can be sustained in large dust grains without fragmentation or complete phase change occuring. In this class of events the cross-sectional area of the impinging dust grain and the thickness of the target are important components of the interaction. The surface area over which a force is administered and the length of time in which the impulse is delivered define the magnitude and the duration of the pressure pulse which gives rise to a sustained shock front in the material.

The duration of the shock front will also be determined by the depth of penetration and therefore the thickness of the target, T_f. If one considers the dynamics of an impact event from the perspective of a penetrating particle the ratio which defines the aspect ratio of the dust grain, i.e., L/D_p, may be investigated to determine the residual length of the particle after encounter with a thin target. In the case of a thin film penetration event, the ratio of interest is that between the diameter of the dust grain, Dp, and the thickness of the film, T_f. It has been well documented (Ref. 5) that a projectile with a high aspect ratio will penetrate to a depth defined by the following relationship:

$$p = L \left(\frac{\rho_P}{\rho_T}\right)^{0.5} \tag{1}$$

The penetration depth, p, of a rod into a thin film can be equated with the film thickness, T_f, and the residual length L_R of the penetrating rod can be equated with the residual diameter of the dust grain. The change in the diameter of the dust grain can be roughly estimated to be:

$$\frac{L_R}{D_p} \sim 1 - \frac{T_f}{D_p} \left(\frac{\rho_T}{\rho_P}\right)^{0.5} \tag{2}$$

In the case of a ratio of $D_p/T_f = 30$ the residual diameter of the dust grain would be greater than 90% by this estimation. Even though the uneroded nature of the material composing the incident dust grain can only be assessed by other measurement means, the foregoing analogy may serve as a metric for further analysis.

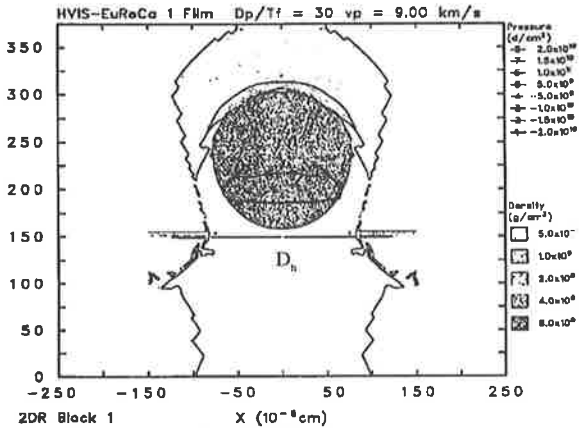

Figure 2. CTH impact simulation; thin film $D_p/T_f = 30$.

Of particular interest in these investigations is a specific empirical form which relates penetration hole size with the diameter of the penetration hole. This experimentally derived equation for the description of the penetration relationship for iron projectiles impacting aluminum films of various thicknesses was developed by Carey, McDonnell, and Dixon (CMD) (Ref. 6). The Carey, McDonnell & Dixon (CMD) empirical equation has been compared with the results of computer simulation of hypervelocity impacts and has been plotted in the following graphs for the velocity of interest for surfaces flown in LEO, i.e., 7 km/s.

$$\frac{D_h}{D_p} = 1 + 1.5 \left(\frac{T_f}{D_p}\right) v^{0.3} \left(\frac{1}{1 + \left(\frac{T_f}{D_p}\right)^2 v^{-n}}\right); \tag{3}$$

$$n = 1.02 - 4 \exp\left(-0.9\, v^{0.9}\right) - 0.003\,(20 - v)$$

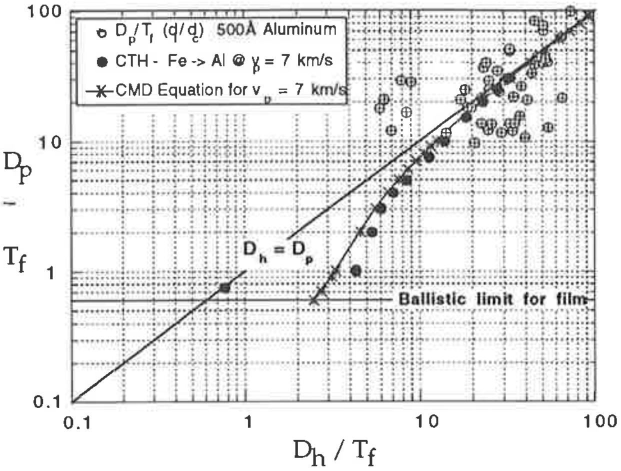

Figure 3. CTH and CMD calulations with impact data.

5. EXPERIMENTAL RESULTS

Results of both two-dimensional (2D) and three-dimensional (3D) computer simulations of the hypervelocity impact events which penetrate the STS and the EuReCa 1 thin films have been reported (Ref. 4 and Ref. 7). A relationship between the particle diameter, D_p, and the diameter, D_h, of the hole created in a 500 Å aluminum thin film (T_f) and micropore foam (T_m) for relevant particle and target parameters will be derived and will be compared with empirical equations. That relationship will be used to analyze *in situ* data of the thin film experiments flown in LEO, and to determine the size distribution of grains which penetrate thin films and are captured intact in micropore foam (Ref 7).

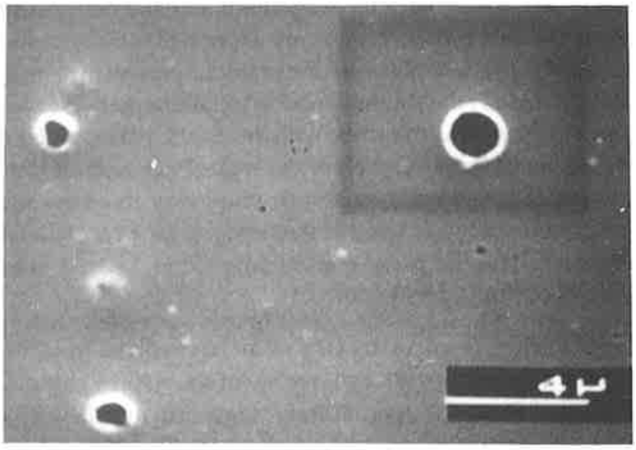

Figure 4. Penetrations in 500Å aluminum film.

Impact sites were created in 500Å Aluminum film using the 2MV Van der Graff Dust Accelerator facility at the University of Kent at Canterbury, Unit for Space Science. The primary purpose was to test an experiment designed to describe the penetration properties of the thin film flown on the US Space Shuttle and the EuReCa/TiCCE. The measurement of the perforations of the film provieds the necessary information to establish the diameter of the impacting dust grain. Hypervelocity impacts also will liberate charge which can be detected by the use of "low-noise" charge sensing amplifiers.

Features on the film pose many problems for the measurement process, since impacts must be distinguished from defects received during the manufacturing process. The task was complicated by the fact that the size distribution of the dust accelerated is dominated by particles large enough to perforated the 500Å of aluminum without generating significant cratering. Craters of varying dimensions which have been identified during a low power scan have been measured at higher magnification to insure that an accurate measurement has been made. The specific dimensions of the crater which were of interest were the average total diameter of the feature (including "lips"), d_c, and the average diameter of the perforation, d_h, if any. Taking the difference of the two average areas obtained from the two diameters yields an estimate of the area associated with the lips of the crater, A_l.

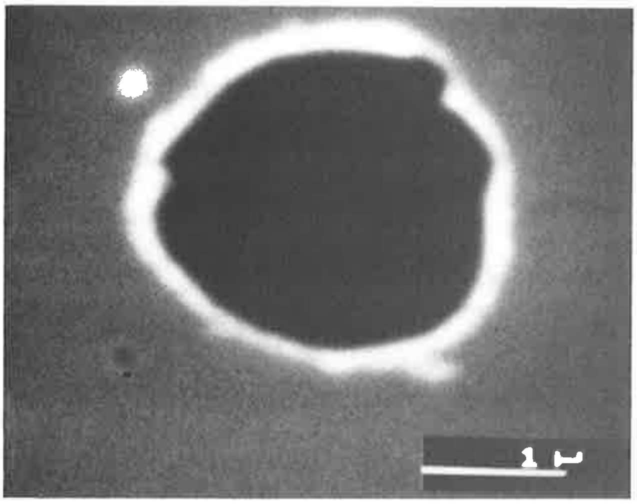

Figure 5. Penetrations in 500Å aluminum film

Thin film perforation events liberate a substantial quantity of charge which can be collected near the impact site. The collection sites can be so subdivided that a location in a plane can be established with high accuracy. However, in order to provide the highest confidence for the survival of a dust grain while penetrating a thin film, the thickness and the density of the material composing the film should be minimized. The magnitude of charge liberated by a thin film perforation has been assumed to be a strong function of the film thickness. The use of thinner films would thus imply a degradation in the position accuracy, especially for the very smallest dust grains ($d_p < 0.1\mu m$). The preliminary results of experiments conducted at the University of Kent at Canterbury, Unit for Space Science (UKC-USS) indicate that the charge yield by perforation of a 250Å aluminum film is commensurate with a 500Å film (Fig. 6).

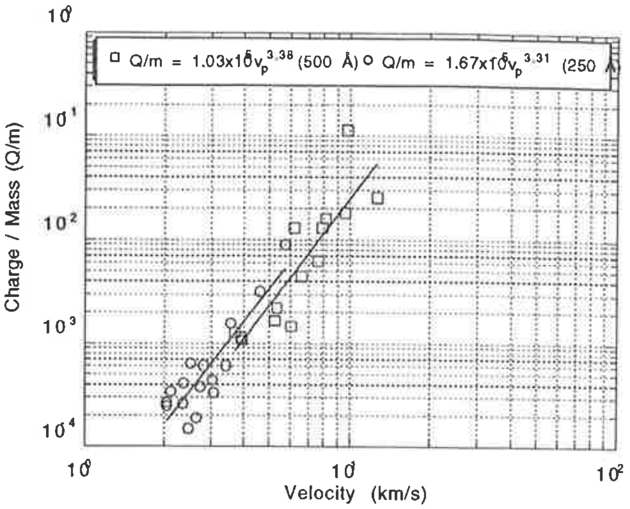

Figure 6. Thin film penetration data for 250Å and 500Å

Further testing will provide data for particle velocities approaching 20 km/s. Each of the thin film perforation events shown above were verified by a charge collection immediately in front of an impact plate situated 5 cm behind the thin film. The coincidence of all sensors recorded the time of flight, electrostatic charge, thin film perforation, and impact charge liberation at the impact plate. These tests constitute an initial calibration of the thin film charge detection system which will provide data depicting the dynamics of grains COMRADE will collect.

5. REFERENCES

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