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The LDCE Particle Impact Experiment as flown on STS-46

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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. Orbital debris models have not been able to describe the flux of particles with $d_p \leq 0.05$ cm, because of the lack of data. Even though LDEF will provide a much needed baseline flux measurement, the continuous monitoring of micron and sub-micron size particles must be carried out.

A flight experiment was conducted on the Space Shuttle as part of the LDCE payload to develop an understanding of the Spatial Density (concentration) as a function of size (mass) for particle sizes 1 X 10^{-6} cm and larger. In addition to the enumeration of particle impacts, it is the intent of the experiment that hypervelocity particles be captured and returned intact. Measurements will be performed post flight to determine the flux density, diameters, and subsequent effects on various optical, thermal control and structural materials.

In addition to these principal measurements, the Particle Impact Experiment (PIE) also provides a structure and sample holders for the exposure of passive material samples to the space environment, e.g., thermal cycling, and atomic oxygen, etc. The experiment will measure the optical property changes of mirrors and will provide the fluence of the ambient atomic oxygen environment to other payload experimenters.

In order to augment the amount of material returned in a form which can be analyzed, the survivability of the experiment as well as the captured particles will be assessed. Using Sandia National Laboratory's hydrodynamic computer code CTH, hypervelocity impacts on the materials which comprise the experiments have been investigated and the progress of these studies are reported.

INTRODUCTION

Orbital debris is becoming a major concern for many of the space systems presently considered. This concern is due to a combination of fundamental issues. The debris environment is a dynamic process in which fragmentation due to collisions create additional objects of different sizes. Collision models combine the effect of pieces reentering the atmosphere and fragmentation due to collisions. Some of the small particles are washed out by solar pressure and some of the larger particles deorbit due to aerodynamic drag, if they are in a low orbit. The size distribution as a function of altitude, of the total effect, is yet unknown but it has been estimated that a uniform increase of 6% over the entire size range envelopes all uncertainties. Immediate detection of meteoroids, orbital debris, and other space debris is extremely important for successful space missions, particularly those of long duration. Impacts may cause damage to manned habitable modules, sensors, reflective or refractive optics, etc. It has been observed that a major source of very small particles come from solid rocket motors (SRM's) fired in space. A single motor, when fired, can emit 10^{20} particles, ranging in size from 1×10^{-4} to 1×10^{-2} cm. Most of these particles, which are aluminum oxide spheres, reenter quickly. However, the small fraction that remain in orbit (~5%/motor/year) produce a flux which exceeds the meteoroid flux, i.e., for a similar size.

Space-based systems exposed to the extreme environment of Low-Earth Orbit (LEO) will avoid catastrophic failures only if the materials which compose them can provide a "shield" against the effects of continuous hypervelocity impacts. Extensive research has been conducted to characterize the effects on materials subjected to hypervelocity impacts by large masses. Even though the large mass impactors carry the highest probability of precipitating a catastrophic event, the number of large mass objects which might be encountered by an exposed surface in LEO is believed to be quite small. However, the size distribution of objects a surface will encounter in LEO has not been adequately characterized; especially for that portion of the distribution which contains the largest number of objects, i.e., the smallest. In order to provide *in-situ* data depicting the size distribution of the most numerous objects in LEO, an experiment has been designed and flown aboard the STS-46 mission.

EXPERIMENTAL DESIGN

Characterization of the orbital debris and micrometeoroid complex 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, the complete analysis of the LEO environment cannot be adequately conducted without repeated examinations of materials which have been exposed to the extremes of space. Hence the experimental design which can provide a much needed investigation of small grains, $D_p \leq 10$ cm, would be a passive sensor which could both detect and capture constituents of the orbital debris and micrometeoroid complex.

Passive Sensor Development

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 STS cargo bay. 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 STS-32 and STS-44 passive sensor experiments was to sample the LEO orbital debris and micrometeoroid complex, an additional design goal for these experiments was to test the survivability of thin films with a thickness of less than 750 Å and which possessed a density of less than 3.0 gm/cm^3. When the ratio of the particle diameter, d_p, to the film thickness, T_f, viz., D_p/T_f, is large and the density of the material composing the film is comparable to the impacting grain ($r_p = r_f$), one can reduce the degree to which the penetrating particle would fragment and thus large fragments or complete grains will impact the plate or capture material below.

STS-46 Experiment

The Center for the Commercial Development of Space: Materials for Space Structures (CCDS) is located at Case Western Reserve University (CWRU), Cleveland, Ohio. CWRU is currently involved in several spaceflight programs to expose materials to the space environment. The Limited Duration Space Environment Candidate Materials Exposure (LDCE) experiment will be launched for CWRU on STS-46. LDCE-1 and -2 are mounted in GAS canisters with door assemblies. LDCE-3 is mounted on the top of the Space Complex Autonomous Payload (CONCAP). Figures 1, 2, and 3 depict the layout of the LDCE-1, -2, and -3 exposure plates prior to integration into the GAS canisters. The PIE sensors are protected by a hard cover (to be removed before flight) and are not visible in the figures. The GAS canisters are located in Bay 13 of OV-104. Figure 4 shows the location of the GAS canisters relative to the other payloads. The samples mounted on LDCE-3 will be 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 will be exposed for a period of forty (40) hours. The exposure will occur towards the end of the mission, near 130 nm, with a continuous payload bay attitude into the velocity vector.

The LDCE will expose numerous samples to the environment. As can be seen in Figure 5, the PIE samples are primarily discs, nominally one (1) inch diameter (4.1 cm^2 exposed area). The discs are held in place, by compression, between highly baked out Nylon washers. Two (2) non-standard size samples were also accommodated.

The LDCE-1 and -3 PIE primarily house sensors for the detection of hypervelocity impacts. The LDCE-1 and -3 PIE sample strips are exact duplicates except for a polished graphite specimen onto which a Niobium grid was deposited. This sample will be used to deduce the LDCE-3 mission atomic oxygen fluence. The LDCE-1 PIE contains a gold foil (nominal T_f ~4.0 μm) that covers a low density micropore foam. The foam has been used on past missions to collect hypervelocity particles, intact. A similar piece of gold foil covers a highly polished aluminum strip coated with vacuum deposited gold. This will aid in the understanding of the distribution of ejecta material. Also included is a thin aluminum film (nominal T_f < 500 Å) stacked above a coated substrate. 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. The last group of passive sensors are high purity metallic surfaces used for the collection of all grains down to sub-micron size. During any impact, a characteristic crater is formed, with rounded habits and a depth to diameter ratio characteristic of the encountered metal. During impact, the particle is destroyed and the remnants are mixed with the target material, concentrating in the bottom of the crater or on the surrounding rims. Its chemical and isotopical properties can be identified by analyzing the rim material.

LDCE-2 contain 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) are used. The LDCE-1 and -2 aluminum films, with a total surface area of 3.24 X 10^{-4} cm^2, should see 5.2 particles 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.

OTHER DEBRIS EXPERIMENTS

Few laboratory hypervelocity impact experiments have investigated the mechanisms of ejecta creation. Consequently, a significant uncertainty accompanies 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. This experiment has been devised to afford opportunities to assess a wide range of the dynamics of ejecta created by hypervelocity impacts on various substrates. Experimental data suggest that an oblique angle hypervelocity impact can create much more ejecta particles than 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. The effects of this energy transfer can be examined through a characterization of the morphological properties of impact craters on witness plates using a Scanning Electron Microscope (SEM), and a digital imagine processing system. In order to examine this phenomenon further, there is a need for an experiment which can capture hypervelocity ejecta so that an ejecta size and velocity distribution may be derived from a non-destructive study. The effects which a variation in the density of the substrate might have on ejecta production must also be investigated. Hydrodynamic and molecular dynamics computer programs will assist in theoretical establishment of relevant hypervelocity impact 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.

As a consequence of the experimental data developed during earlier STS missions and the data expected from this mission, the authors have produced and delivered an experiment for the European Space Agency's European Retrievable Carrier (EuReCa 1) which will provide a nine-month exposure at 500 km for similar thin film experiments. EuReCa 1 is also manifested on STS-46. The data to be returned by the EuReCa 1 experiment will be produced through an examination of the morphology of primary and secondary hypervelocity impact craters. Primary attention will be paid to craters caused by ejecta produced during hypervelocity impacts on different substrates, e.g., gold, aluminum, palladium, and at different angles of incidence, viz., 45°, 35°, 25°, 0°. From these data one will be able to determine the size distribution of ejecta by means of witness plates and collect fragments of ejecta from craters by means of momentum sensitive micropore 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, [given that the ejecta number density is a strong function of the angle taken with respect to the surface normal of the impact target].

COMPUTER SIMULATIONS OF THIN FILM PENETRATION

During the decades ahead, a significant amount of material which 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 orbital debris and micrometeoroid population can be developed. To this end, extensive 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 (IDP's) and orbital debris. Through numerous hypervelocity impact investigations, Baylor University Space Science Laboratory (BUSSL) researchers have accumulated experience which has been applied to hydrodynamic computer program development and the utilization the multi-dimensional hydrodynamics code CTH (McGlaun, S.L. Thompson, and M.G. Elrick ,1990; Thompson and Lauson, 1984) 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 an aluminum thin film [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 STS-46 and EuReCa 1.

EMPIRICAL ESTIMATIONS OF PENETRATION PARAMETERS

Extensive experimental work has established several empirical relationships (McDonnell, Carey, and Dixon, 1984; Carey, McDonnell, and Dixon, 1985) which describe the hypervelocity impact event of thin film penetration. Interpretations of the solutions derived by use of CTH must be substantiated by a clear connection with parameters derived by experiment. Though by no means an exhaustive list of penetration equations, the four listed below are representative equations of the empirically derived penetration limits for thin films. One important aspect about these equations to notice is the apparent continuity between early work dating back to 1965 and even the most recent empirical equations.

Thin Film Penetration Equations:

$$\frac{T_f}{D_p} = 0.055\ D_p^{\ 0.056} \left(\frac{\rho_P}{\rho_T}\right)^{0.476} \left(\frac{\sigma_{Al}}{\sigma_T}\right)^{0.134} V_p^{\ 0.739};$$ McDonnell & Sullivan (1991)

$$\frac{T_f}{D_p} = 0.772\ D_p^{\ 0.2}\ \varepsilon^{-0.06} \rho_p^{\ 0.73} \rho_T^{\ -0.5} (V_p \cos\alpha)^{0.88}$$ Pailer & Grün (1980)

$$\frac{T_f}{D_p} = 0.57\ D_p^{0.056}\ \varepsilon^{-0.056} \left(\frac{\rho_p}{\rho_T}\right)^{0.5} V_p^{0.875}$$ Fish & Summers (1965)

Although not presented here, the above equations have been plotted versus velocity as well as versus particle diameter. In order to analyze by empirical means the penetration parameters of thin films like those flown on STS-46 and EuReCa 1, one may utilize the Fish-Summers (Fish, and Summers, 1965) penetration formula. Given that the thickness of the metallic foil is 5.00 X 10^{-6} cm, density of 2.7 g/cm^3, and velocity of 7 km/s, then the minimum mass which could penetrate the thin film would be:

$$T_f = K\ r_p^{0.148}\ M_p^{0.352}\ V_p^{0.667} \quad \text{or} \quad M_p = \left[\frac{T_f}{K\ r_f^{\ 0.148}\ v_p^{\ 0.667}}\right]^{2.84} = 2.2 \times 10^{-15}\ \text{g},$$

where K = 3.56 x 10^{-4} for aluminum. A recent empirical equation reported by McDonnell (McDonnell et al, 1990) which gives a measure of the penetration limits for metallic films exposed to the LEO orbital debris and micrometeoroid complex can be used to derive the following penetration mass limit:

$$M_p = K''\ T_f^{\ 3} \left[\frac{\rho_p}{\rho_t}\right]^{-0.78} \left[\frac{\sigma_t}{\sigma_0}\right]^{0.24} v_p^{-3\beta} = 1.00 \times 10^{-15}\text{g}\ ; \quad \text{with}\ \beta = 0.69 \left[\frac{\rho_p}{\rho_t}\right]^{0.09}$$

where K" = 2.42 x 10^{-18} is an empirically derived constant. These mass calculations suggest that the thin films can be penetrated by a grain which possesses a mass greater than a picogram. Using a more recent equation (McDonnell and Sullivan, 1991) one finds that :

$$D_p = \frac{T_f}{0.055} \left[\frac{\rho_T}{\rho_P}\right]^{0.476} \left[\frac{\sigma_t}{\sigma_0}\right]^{0.134} v_p^{-0.739} = 3.82 \times 10^{-7}\text{m};\ M_p = 7.91 \times 10^{-14}\text{g}.$$

Of particular interest to 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) (Carey, McDonnell, and Dixon, 1985). The Carey, McDonnell & Dixon (CMD) empirical equation has been compared with the results of computer simulation of hypervelocity impacts, and has been plotted for various velocities of interest for surfaces flown in LEO. The CMD equation is shown as:

$$\frac{D_h}{D_p} = 1 + 1.5\left(\frac{T_f}{D_p}\right) v_p^{0.3} \left(\frac{1}{1 + \left(\frac{T_f}{D_p}\right)^2 v_p^{-n}}\right)\ ; \text{Where}\ n = 1.02 - 4\exp\left(-0.9\ v_p^{0.9}\right) - 0.003\ (20 - v_p)$$

The most general form of the CMD equation utilizes the ratio of the target density to the particle density raised to the 0.6.

$$\frac{D_h}{D_p} = 1 + 2.9\left(\frac{\rho_f}{\rho_p}\right)^{0.6}\left(\frac{T_f}{D_p}\right) v_p^{0.3}\left(\frac{1}{1 + 2.9\left(\frac{\rho_f}{\rho_p}\right)^{0.6}\left(\frac{T_f}{D_p}\right)^2 v_p^{-n}}\right);$$

where n is unchanged.

SUMMARY

Data from two-dimensional (2D) computer simulations of the hypervelocity impact events which will most probably penetrate the STS-46 and the EuReCa 1 thin films conform to a high degree with the CMD equation, for all densities tested. The CMD 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) for relevant particle and film parameters when compared with other thin film penetration data, is found to agree. 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 extended computer simulations suggest that the CMD relationship may be used to analyze *in-situ* data of the thin film experiments flown on LDCE, and to determine the size distribution of particles which penetrate the thin films.

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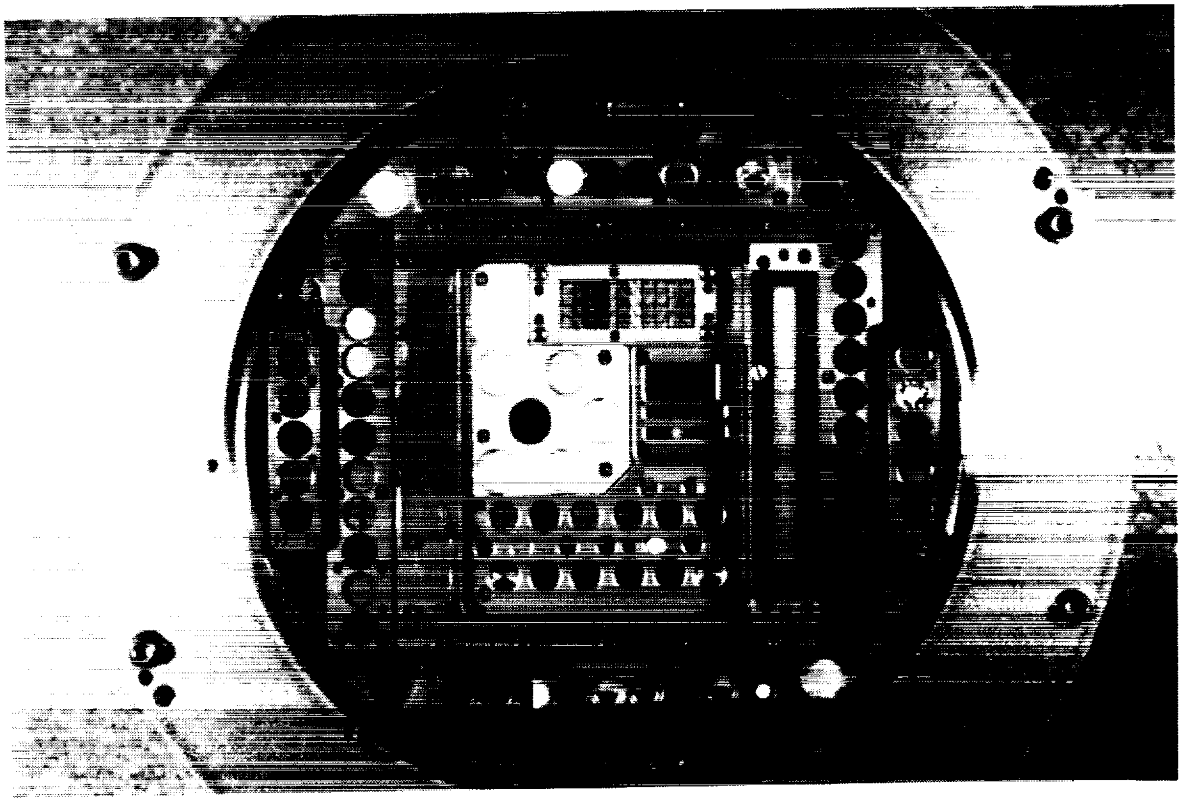

Figure 1. LDCE-1 Exposure Plate Prior to Integration

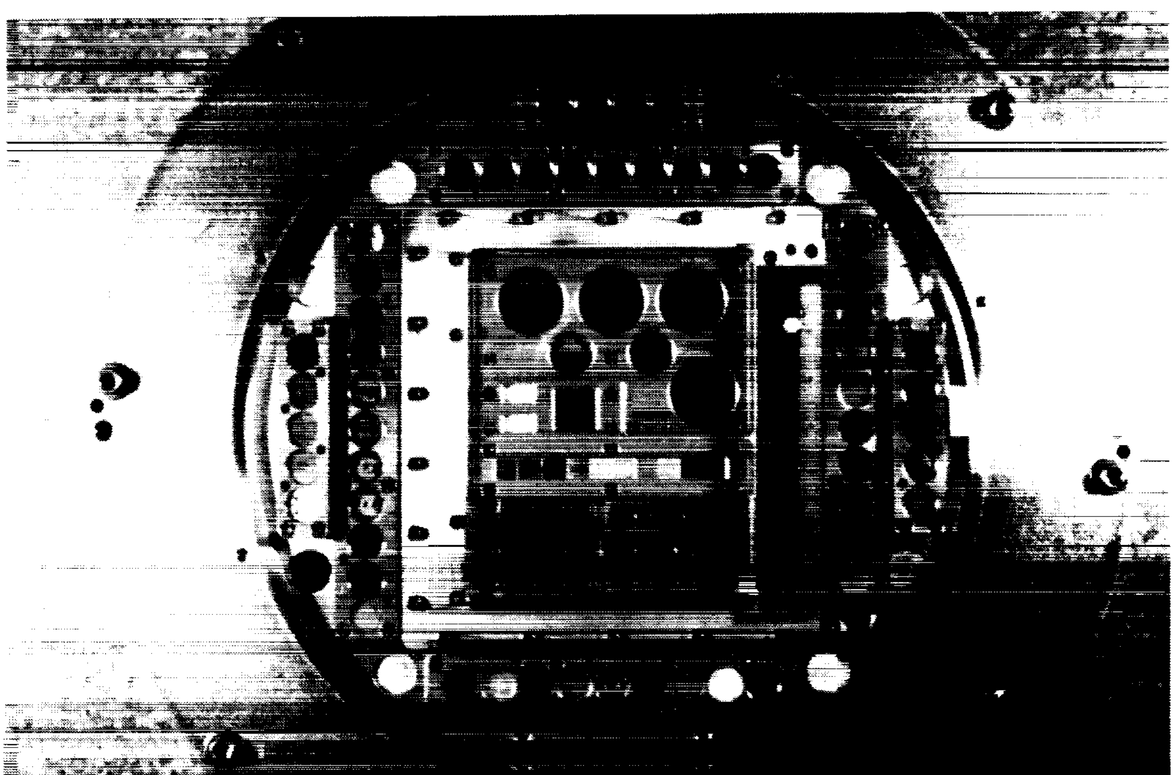

Figure 2. LDCE-2 Exposure Plate Prior to Integration

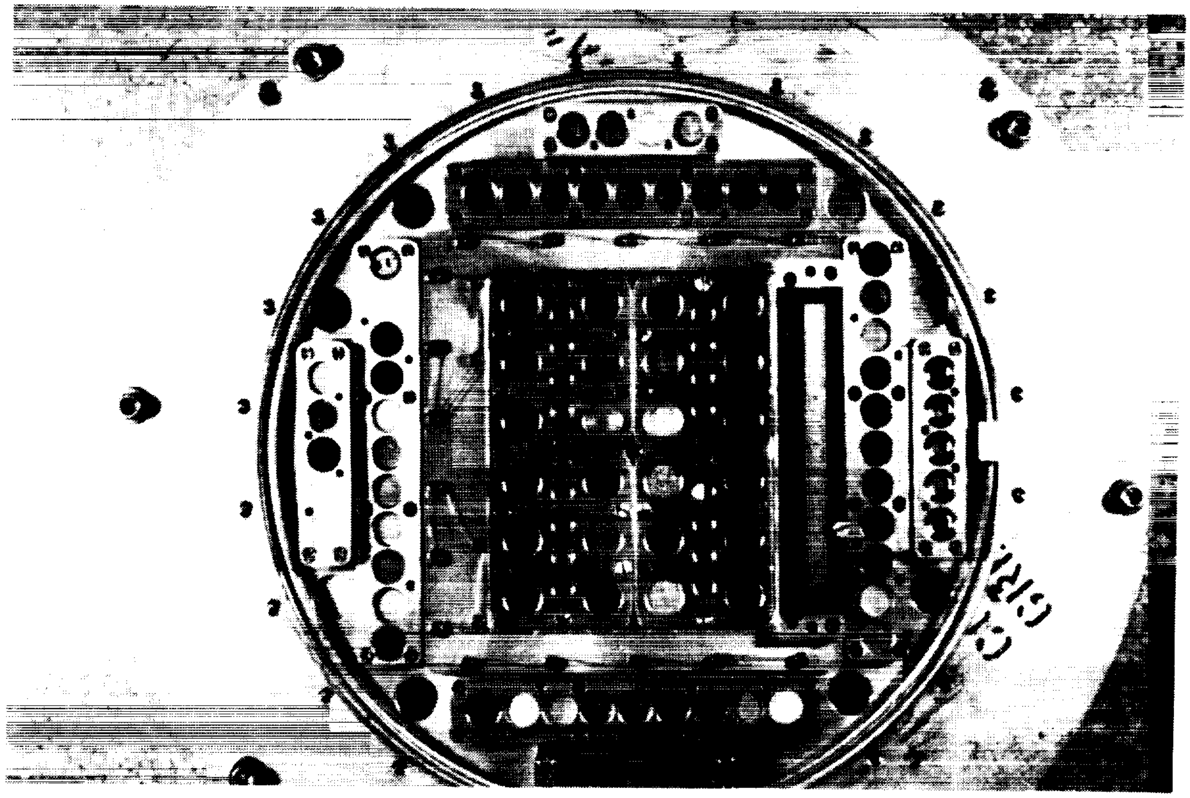

Figure 3. LDCE-3 Exposure Plate Prior to Integration

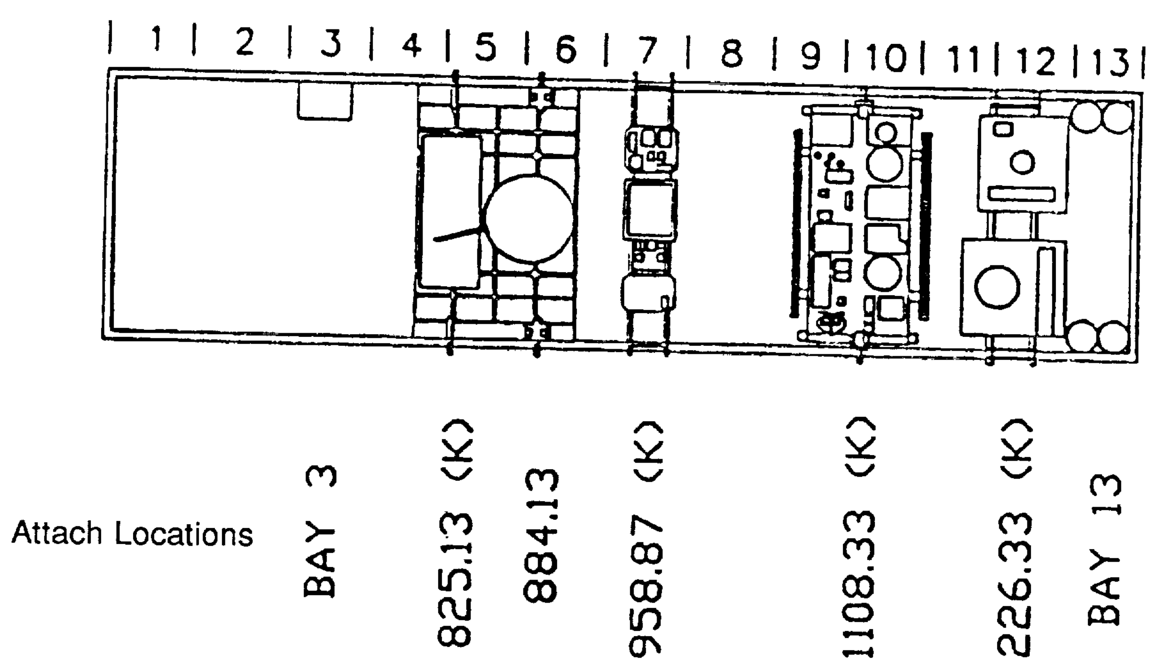

Figure 4. GAS Canister Locations: OV-104, Bay 13.

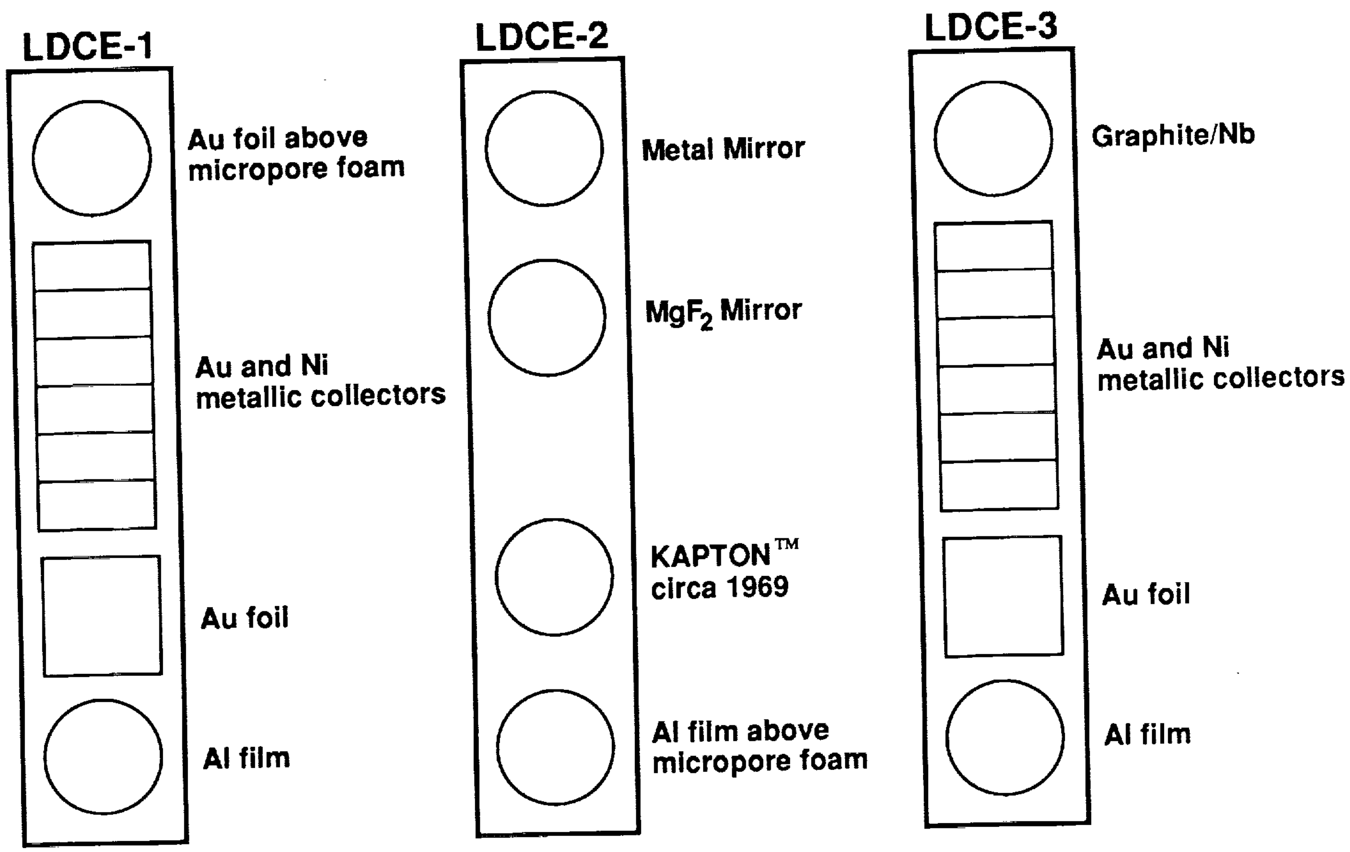

Figure 5. PIE Sample Mounting for LDCE-1, -2, and -3.