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MEASURED SPACE ENVIRONMENTAL EFFECTS TO LDEF DURING RETRIEVAL

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SUMMARY

On the STS-32 shuttle mission, a space flight experiment provided an understanding of the effects of the space environment on the Long Duration Exposure Facility (LDEF) from rendezvous with the shuttle until removal from the payload bay at the Orbiter Processing Facility (OPF) at NASA/KSC. The Interim Operational Contamination Monitor (IOCM) is an attached shuttle payload that has been used on two (2) earlier flights (STS 51C and STS 28) to quantify the contamination deposited during the course of the missions.

The IOCM can characterize by direct measurement the deposition of molecular and particulate contamination during any phase of flight. In addition to these principal measurements, the IOCM actively measures the thermophysical properties of thermal control surfaces by calorimetry, the flux of the ambient atomic oxygen environment, the incident solar flux, and the absolute ambient pressure in the payload bay. The IOCM also provides a structure and sample holders for the exposure of passive material samples to the space environment, e.g., thermal cycling, atomic oxygen, and micrometeoroids and/or orbital debris, etc.

One of the more salient results from the STS-32 flight suggests that the LDEF emitted a large number of particulates after berthing into the shuttle. The mission atomic oxygen fluence was also calculated. Although the fluence was low by normal standards, the Kapton™ passive samples exhibited the onset of erosion. Orbital debris and micrometeoroid impacts also occurred during the retrieval mission. The average perforation diameter was ~12.5 µm. The largest perforation diameter was measured at 65 µm.

INTRODUCTION

In the recent years of unmanned spaceflight, contamination has become a recognized source of spacecraft anomalies and failures. This realization was due in part to experience and failure analysis, and in part to the development of more sophisticated subsystems and instruments, which were more sensitive to the effects of contaminants.

Contamination may be classified approximately as molecular or particulate. In this classification, free molecular contaminants are in the gas phase, and free particulates are solids or liquid droplets. In their free forms, contaminants in the field-of-view of subsystems and instruments cause the attenuation scattering of electromagnetic radiation. Particulates reflect sunlight and may confuse star trackers by appearing as false stars. More importantly, the contaminants may deposit on sensitive surfaces. In the deposited form, solid discrete particulates can partially obscure optical surfaces and cause flare and off-axis scattering. Liquid droplets and gases deposit in layers on surfaces, especially cold ones. Both types of contamination may then change the optical, electrical, and thermal properties of the surface material. The latter effect on thermal control surfaces may be the best known spacecraft anomaly. Historical interpretations range from operating temperature increases due to the gradual degradation of thermal control surfaces, to the loss of a spacecraft from a propellant line or valve rupture caused by the deposition of Solid Rocket Motor (SRM) plume effluents.

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Scientific instruments and optical sensors are typically more sensitive to contamination than spacecraft subsystems. Thus, the space science community raised the issue of contamination early in the development of the Space Transportation System. For an unmanned spacecraft or satellite, the Shuttle presents several unique contamination issues. Leakage, venting and dumping from a manned system represent contaminant species not usually encountered. The Orbiter cargo bay provides for the launch systems unprotected by an aerodynamic shroud, which traditionally provided a contamination barrier to the launch vehicle. The Orbiter also functions as a large, complex space platform for instruments. Finally, the shared cargo bay creates a new concern, inter-payload contamination.

The space experimenters, in a NASA advisory group, considered these issues and determined that the most stringent Shuttle-specific requirements were needed in the area of instrumental background presented by the Orbiter. Their recommendations for upper limits on molecular species column densities and particle sighting rates were based on the sensitivity of their instruments. This effort led to an attempt to design a clean Orbiter cargo bay. The greatest success has been the selection of materials which produce little molecular contamination (low outgassing).

As a result of this interest, the United States Air Force/Space Systems Division (OL-AW) sponsored the development of the Interim Operational Contamination Monitor (IOCM). The IOCM's purpose was to provide verification measurements of Orbiter contamination for specific payloads. The IOCM is an automatically operating system for the measurement of particulate and molecular contamination that may be present in the shuttle cargo bay during the period from before launch until after landing. The IOCM has successfully flown on two earlier flights: STS 51-C and STS-28 . Excellent data has been obtained on gaseous and particulate contaminants and their effects on materials. The IOCM has demonstrated that Orbiters with mostly empty bays and proper ground processing can meet the NASA goals, but with significant variability. In its latest flight during the LDEF retrieval, the IOCM showed its capability to provide quality data from pre-launch to payload removal.

SYSTEM CAPABILITY

The IOCM can characterize by direct measurement the deposition of molecular and particulate contamination during any phase of flight, i.e., pre-launch, ascent, on-orbit operations, descent and ferry flight of the shuttle. Measurements can be, and usually are, made continually during these periods. The molecular contamination is further classified in terms of the temperature of the surface (a pre-programmed function) on which it is deposited and from which it is re-emitted. Two types of particulate collection sensors are employed in order to avoid efficiency of collection uncertainties. One of these sensors is also capable of studying the temperature effect on the efficiency of collection.

The IOCM is of a modular design capable of molecular and particulate contamination measurements at multiple physical locations in the shuttle cargo bay. The modules provide for measurements on the various Cartesian axes of the Orbiter by the use of multiple identical sensors. In addition to these principal measurements, the IOCM actively measures the optical property changes of thermal control surfaces by calorimetry, the flux of the ambient atomic oxygen environment, the incident solar flux, and the absolute ambient pressure in the payload bay. The IOCM also provides a structure and sample holders for the exposure of passive material samples to the space environment, e.g., thermal cycling, atomic oxygen, and micrometeoroids and/or orbital debris, etc.

SYSTEM DESCRIPTION

The IOCM is an attached shuttle payload. In its baseline configuration, it is usually mounted on three (3) Adaptive Payload Carriers (APC's) in the cargo bay. The mounting locations are determined for each specific flight on which the IOCM is manifested. For STS-32, the IOCM was mounted on a Get-Away Special (GAS) Adapter Beam and installed on the starboard side in Bay two (2). The system is selfcontained except for an Orbiter power interface. The system is designed for no crew involvement and for no command and control support.

IOCM Functional Description

The IOCM provides for the continuous measurement of collected particulate and molecular mass at preprogrammed collection surface temperatures during the time period from power-up (prelaunch) until power-down (post-landing). A Programmed Read Only Memory (PROM) provides the operational command profile for the IOCM during all mission phases.

IOCM STS-32 Elemental Description

The baseline design of the IOCM consists of six (6) equipment modules mounted on three (3) APC's. For STS-32, the sensors from the six (6) equipment modules were relocated and condensed into one carrier so as to provide the maximum amount of data to the LDEF principal investigators and to the LDEF project office. Figure 1 depicts the IOCM hardware mounted in the shuttle bay during the STS-32 flight. A description of the more salient sensors is provided in the following paragraphs.

The IOCM, as flown on STS-32, contained nine (9) actively controlled contamination sensors: six (6) Temperature-controlled Quartz Crystal Microbalances (TQCMs), two (2) particle capture (PARCAP) devices, and one thermal coatings calorimeter. Also included were two nude ionization pressure gauges for sensing and measuring ambient pressure (10^{-3} to 10^{-8} torr), three solar flux gauges (light-intensity sensors), and temperature sensors for internal housekeeping.

The TQCMs measure contamination by means of a frequency shift of a quartz crystal oscillator. This occurs when the crystal mass increases as a result of contamination accretion. The device is extremely sensitive, 1 Hz corresponding to 1.56×10^{-9} g/cm^2. This sensitivity is achieved by using a specially cut crystal which produces an extremely small temperature dependence and by using a reference quartz crystal. The signal from the reference quartz crystal, when mixed with the signal from the sensing crystal, gives a beat frequency totally independent of temperature and power supply fluctuations.

The TQCMs were manufactured by Faraday Laboratories, Inc., La Jolla, California. The sensor consists of a matched pair of quartz crystals; each resonates at approximately 15 MHz. The crystals are designated as sensor and reference crystal. The sensing crystal is displaced in frequency approximately 1 KHz below the reference crystal. The crystals are optically polished and plated with gold. The output of a mixer circuit provides a frequency which increases when the sensing crystal is contaminated. In addition, a two-stage thermoelectric device is located directly behind the crystals to allow for the cooling or heating of the sensor quartz crystals. The thermoelectric device will control the temperature of the sensor crystals between -50°C and +100°C to ±1°C when its heat sink is maintained below +40°C.

The Thermal Coating Calorimeter is a refined version of the type developed by NASA/GSFC. This device can measure discrete changes in the thermal radiative properties of the coatings applied to the calorimeter. Similar units have successfully flown on numerous missions including the IOCM, NOAA-C and NOVA contamination monitor projects. The thermal coating on the calorimeter was a second surface type mirror SiO_2/Ag). These mirrors are also known as Optical Solar Reflectors (OSRs). This surface was designed to act as the primary contamination effects monitor.

Passive Sample Array

The Passive Sample Array (PSA) is a passive structure designed to expose selected material samples to the Orbiter bay environment. Figure 2 shows an oblique view of the samples. This array contained samples to help understand what additional environmental damage (if any) occurred to LDEF during the retrieval mission. Table 1 shows the participating organizations.

SIGNIFICANT ACTIVE SENSOR FLIGHT DATA

TQCM 1 was mounted in the IOCM facing toward the forward bulkhead (+ X direction). The intent of this sensor was to observe molecular species from the forward bulkhead area.

Figure 3 shows an end-to-end plot of TQCM 1 during the on-orbit phase of the mission. The data suggests exposure to a high flux of condensible material. It should be re-emphasized that the temperature of the sensors was at 15° C until 12 hours into the mission. At this time, the temperature was reduced to 0°C. Data suggests that an event centered near 42.5 hours caused this mass deposition.

Examination of Table 2 suggests that the COAS maneuver (a manual IMU alignment) is the source of this deposition. The maneuver rotates the Orbiter from the -ZLV attitude to the +XLV attitude over a period of 38 minutes. This places the payload bay into the velocity vector while using the vernier thrusters. This suggests that these species are returning to the shuttle payload bay. Figure 4 shows a less course portion of the data. The data is centered about the event at 42.5 hours. Examination of the temperature data shows that the programmed cleaning cycle occurs after the deposition. The deposition could not be removed by a temperature of 80° C. Figure 4 also shows an increase in mass occurring at about 29 hours. Table 2 also indicates an OMS burn occurring at this period of time. Maximum deposition was 0.70 $\mu g/cm^2$ at approximately 42.5 hours into the flight. Some re-emission occurred after the bakeout of the crystals. This strongly suggests that the deposited mass has a reasonably high molecular weight.

TQCM 5 was mounted on the IOCM facing across bay (+Y,-X direction). The intent of this sensor was to observe particulate and molecular species as incident flux during the mission. The sensor looks aft at a 45° angle. Figure 5 shows an end-to-end plot of the mass accumulation after lift-off. As can be seen, numerous events occurred during the course of the mission to affect the mass accumulation.

The onset of mass deposition can be seen at the 42.5 hour time period (COAS maneuver). Figure 5 shows the increase in mass deposition and the subsequent re-emission of material after cleaning of the sensor crystals. The total mass deposition from this event was 0.78 $\mu g/cm^2$. After sensor burn-off, an additional 0.47 $\mu g/cm^2$ remained.

Figure 5 also shows the accumulation of material on this sensor from latchup through the end of the on-orbit phase of the mission. The mass accumulation on the sensor is indicative of the mass loss from the LDEF. The data suggests that the average mass loss rate is 2.38×10^{-12} g/cm^2-sec.

TQCM 6 is also mounted on the IOCM facing across bay (+Y,-X direction). The intent of this sensor was also to observe molecular species as incident flux during the mission. The sensor is mounted next to TQCM 5 and accordingly, looks aft at a 45° angle.

Figure 6 shows an end-to-end plot of the mass accumulation after lift-off. As can be seen, numerous events occurred during the course of the mission to affect the mass accumulation on this sensor. This sensor was also cleaned with a high temperature bakeout of the crystals.

As observed on other sensors, the onset of mass deposition can be seen at the 42.5 hour time period (COAS maneuver). Figure 6 shows the increase in mass deposition and the subsequent re-emission of material after cleaning of the sensor crystals. The total mass deposition from this event was 0.60 $\mu g/cm^2$. After sensor burn-off a negligible (0.003 $\mu g/cm^2$) amount remained.

Figure 6 also shows the accumulations of material on this sensor from latchup through the end of the on-orbit phase of the mission. The mass accumulation on the sensor is, again, indicative of the mass loss from the LDEF. The data suggests that the average mass loss rate is 2.53×10^{-12} g/cm^2-sec. The data from TQCM 6 agrees quite well with that of TQCM 5.

The thermal coating calorimeter operated as designed and has provided insight in the effects of contamination from the bipropellant thrusters. Figure 7 shows the mission temperature profile. The range of the sensor is between -50° C and +50° C. The sensor initially averaged -22.2° C. The lowest temperature recorded was -50.0° C. The absolute temperature of the calorimeter was obviously lower than the recorded temperature. The lower temperatures occurred during maneuvers to rendezvous and latchup LDEF. One interesting observation is the obvious change in temperature after the 42.5 hour time period, i.e., after the COAS maneuver. The temperature increased to and leveled at an average of -18.8° C, subsequently dropping near the end of the mission to an average of -19.1° C. This data suggests that the effective solar absorptance (α_s) of the OSR increased from 0.100 to 0.107 in approximately 80 hours. It should be noted that the calorimeter equilibrium temperature was approximately 20° C colder than the TQCM set temperature, thus allowing more mass to deposit during the COAS maneuver. During the cool down of the calorimeter, in the latter portion of the mission, an estimate of the hemispherical emittance (ε_{th}) was made. The value agrees within 1% (absolute) of the measured value, i.e, 0.76.

ACTIVE SENSOR POSTFLIGHT DATA

One of the IOCM goals was to provide an understanding of the environment experienced postflight to the LDEF. In order to provide this information the IOCM required power at all facilities at which the orbiter would be located after landing. It is our understanding that the combination of positive pressure within the PLB and the opening of the airlock hatch to place additional instrumentation created a "snowstorm" of the particulates that were sloughing/shedding from LDEF. This event compromised the postflight data.

In general, the ferry flight did not contribute to the overall contamination of the LDEF. The most deleterious impact occurred within the last 24 hours at Julian day 030. This appears to be the period when the strongback was placed over the PLB.

PASSIVE ARRAY DATA

The IOCM exposed twenty-five (25) samples to the environment. As can be seen in Figure 1, the samples were mounted facing out of the payload bay. The discs are 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. Three (3) non-standard size samples were accommodated in the array. The majority of the samples were selected from a list generated by a request placed to NASA centers, USAF laboratories, Universities and European space R&D centers.

Figure 8 shows one of the many impact films flown in the passive array. The film is one (1) mil black Kapton™. Figure 9 shows an impact site observed postflight. The perforation is ~1 µm diameter. One of the more interesting observations seen on this sample is the micron and sub-micron sized particles and agglomerates on the surface. The analysis of the particles show the majority to be Aluminum. It is obvious that the material deposited on the surface after the impacts occurred. Particles are evident both on the edge and in the interior of the perforation. Figure 10 shows a perforation through a sample of two (2) mil Kapton™. Also evident is a sub-micron perforation along with micron and sub-micron sized particles and agglomerates on the surface. Table 3 provides a catalog of observed perforations during the mission.

Coatings of inorganic silicon compounds (oxide, p-SiO_2 and amorphous hydrogenated silicon, α:Si:H) over Kapton™ were exposed during the experiment by the Canadian Space Agency. As a reference standard, an uncoated specimen of Kapton™ was also included. Analysis of the exposed surface of the uncoated Kapton™ using the Scanning Electron Microscope (SEM) showed that the threshold fluence after which Kapton™ erodes had just been exceeded. The uncoated Kapton™ surface had begun to pit and erode in Figure 11, but had not yet developed the familiar rug-like pattern. From this degree of erosion it is possible to estimate that the fluence of atomic oxygen seen by the specimens was approximately 10^{19} atoms/cm^2. In contrast, surface analysis of the coated specimens of Kapton™ showed no deleterious effects of the space environment exposure on either material coating.

Results of samples flown by NASA/LeRC indicate that low, but observable, atomic oxygen interaction has occurred on the samples. Uncoated polyimide Kapton™ films have developed a very small surface texture. At the sites of defects in protective coatings over polyimide such texture can also be observed. Figure 12 shows these defects and the underlying "carpet-like" morphology typical of the onset of AO erosion of Kapton™. Table 4 provides a comparison of Kapton™ films exposed during the mission.

CONCLUSIONS

Based on the data gathered by the IOCM [1], it is felt that the instrument performed extremely well and met or exceeded its goals. The active and passive sensors, in concert with analytical chemistry techniques, have provided a wealth of information on the effect of the environment to STS-32 and the LDEF.

Two of the more salient observations made during the period of active sensor operation were the fact that the IOCM observed what appears to be prelaunch contamination and that the "return flux" phenomena first seen on the STS-3 OSS-1 Contamination Monitor Package was observed again. The data also confirms the fact that the payload bay was in an extremely clean condition when launched. Return flux from the Orbiter RCS system has been observed. The resultant deposition required a high temperature bakeout to initiate removal of the accreted mass. The deposit increased the solar absorptance of the calorimeter sample by 0.007.

In addition, the Orbiter did not appear to contribute to the gaseous environment as observed by the active sensors. On the other hand, LDEF acted as a large source of contamination (mainly micron and sub-micron sized particulates) to the shuttle. The source emission rate of LDEF averaged 2.5×10^{-12} g/cm^2-sec for a period of eighty hours following berthing, falling off to a rate of 4.1×10^{-13} g/cm^2-sec just prior to re-entry. Postflight obscuration ratios on IOCM surfaces were measured at 2.4 percent. The LDEF appears to have contaminated itself, principally after landing.

The mission atomic oxygen fluence was calculated to be 2×10^{19} atoms/cm^2. Although the fluence is low by normal standards, the Kapton™ passive samples on the IOCM exhibited the onset of erosion. Trailing edge trays of the LDEF should be examined for the onset of erosion. Orbital debris and micrometeoroid impact plates suggest a flux of 6×10^2 impacts/m^2 occurred during the mission, with an average perforation diameter of ~12.5 μm. The largest perforation diameter was measured at 65 μm.

Measurements of contamination during the postflight phases, i.e., ferry flight and de-integration processing in the OPF, show negligible to very low particle transfer, respectively. Obscuration ratios during ferry flight were calculated at 0.2 percent on horizontal surfaces. The largest mass deposition occurred during activities in the OPF.

The reduction of the sensor data confirmed what was self-evident upon opening the payload bay doors in the OPF. The LDEF was shedding significant amounts of ultrafine particulate material. This material was identified as residue of aluminized Mylar thermal blankets.

REFERENCES

1. Maag, C.R., "Results of the Interim Operational Contamination Monitor (IOCM) as Flown on the STS-32 Mission". Final Report JPL D-8170, March 1991.

TABLES

TABLE 1. PASSIVE ARRAY PARTICIPATING ORGANIZATIONS

ORBITAL DEBRIS IMPACTS

- UNIVERSITY OF KENT (UK)
  - Aerogel
  - Aluminum Foil
- INSTITUT d'ASTROPHYSIQUE SPATIALE (FR)
  - Gold Foils
  - Nickel Foils
- BAYLOR UNIVERSITY (USA)
  - Aluminum Films
- SCIENCE APPLICATIONS INTERNATIONAL CORP. (USA)
  - Polyimide Film

ATOMIC OXYGEN EROSION

- NASA/LeRC (USA)
  - Coated Polyimide Films
- CANADIAN SPACE AGENCY
  - Coated Polyimide Films
- NASA/JPL (USA)
  - Polyimide Films
  - Teflon Films
- UNIVERSITY OF ALABAMA @ HUNTSVILLE (USA)
  - Carbon
  - Fused Silica
- DU PONT (USA)
  - Coated Polyimide Films
- SCIENCE APPLICATIONS INTERNATIONAL CORP. (USA)
  - Polyimide Film

CONTAMINATION

- NASA/JPL (USA)
  - Germanium (IRE) Crystals
- NASA/MSFC (USA)
  - UV Mirrors

TABLE 2. STS-32 TIMETABLE OF MAJOR EVENTS

R1 A1 SW30 ENABLED	T minus 43 hours
PLB DOOR OPENING	T plus 1.6 hours
SYNCOM IV DEPLOY	T plus 24.7 hours
SYNCOM BURN/STAGING	T plus 25.5-27.5 hours
NORMAL CORRECTION BURN	T plus 29.0 hours
FIRST WATER DUMP	T plus 42.0 hours
OMS BURN	T plus 42.5 hours
LDEF LATCHUP	T plus 74.7 hours
LDEF BERTHING	T plus 80.0 hours

TABLE 3. CATALOG OF OBSERVED PERFORATIONS

d (μm)*	N**
.1	TBR
1	384
5	320
10	256
20	64
40	32
65	32
• Average Perforation Diameter: ~ 12.5 μm	
• Maximum Perforation Diameter: ~ 65.0 μm	

* Equal to or less than

** Approximate number of impacts/m^2

TABLE 4. COMPARISON OF KAPTON FILMS DURING STS-32 MISSION

INVESTIGATOR	ESTIMATED MISSION FLUENCE*	ESTIMATED TRAILING EDGE FLUENCE
B. BANKS (NASA)	NONE	$\sim 2 \cdot 10^{17}$ atoms/cm^2
C. MAAG (SAIC)	$\sim 9 \cdot 10^{18} - 2 \cdot 10^{19}$ atoms/cm^2	NONE
D. ZIMCIK (CSA)	$\sim 2 \cdot 10^{19}$ atoms/cm^2	NONE

*Best estimate from erosion

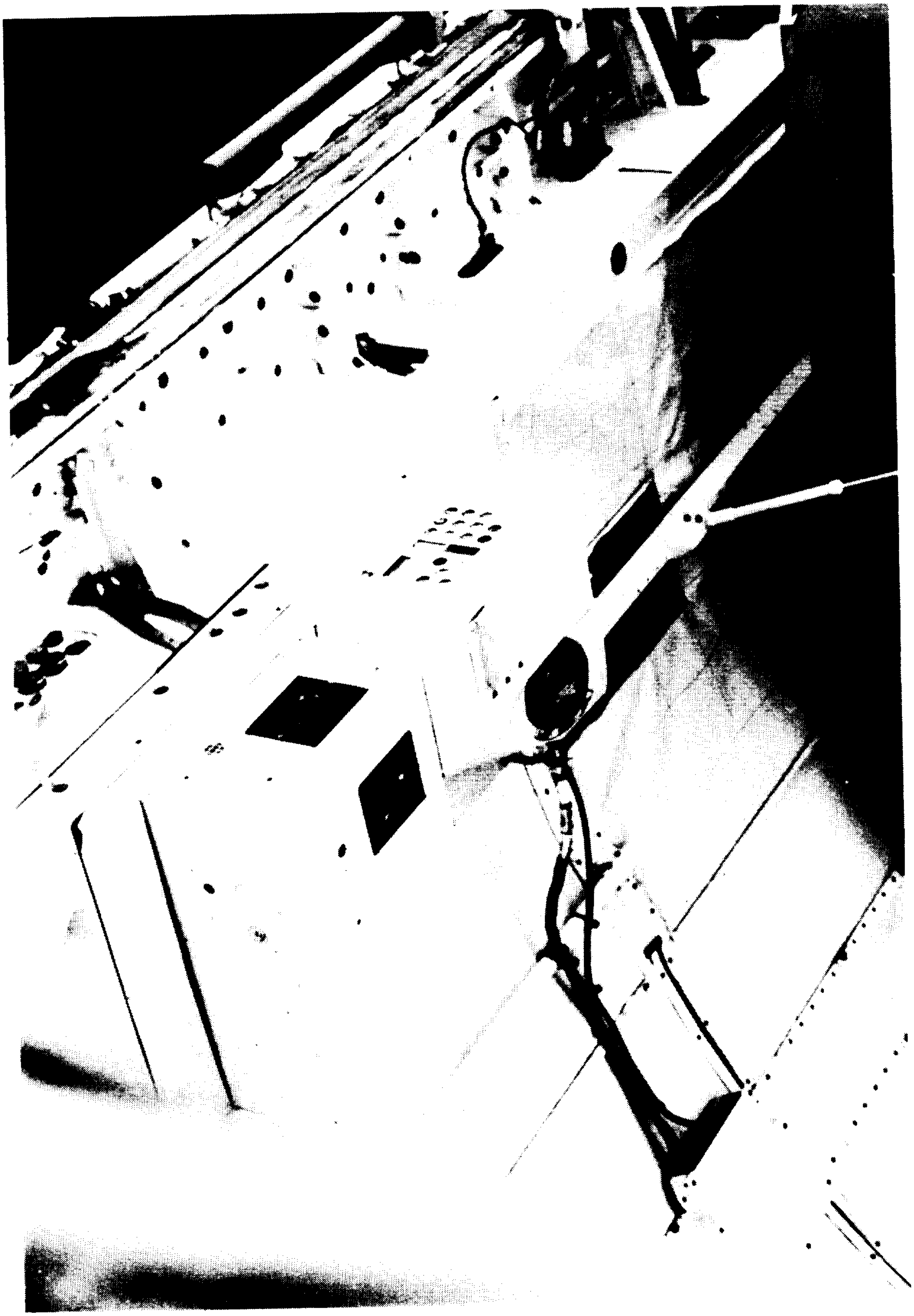

FIGURE 1. IOCM HARDWARE MOUNTED IN SHUTTLE BAY

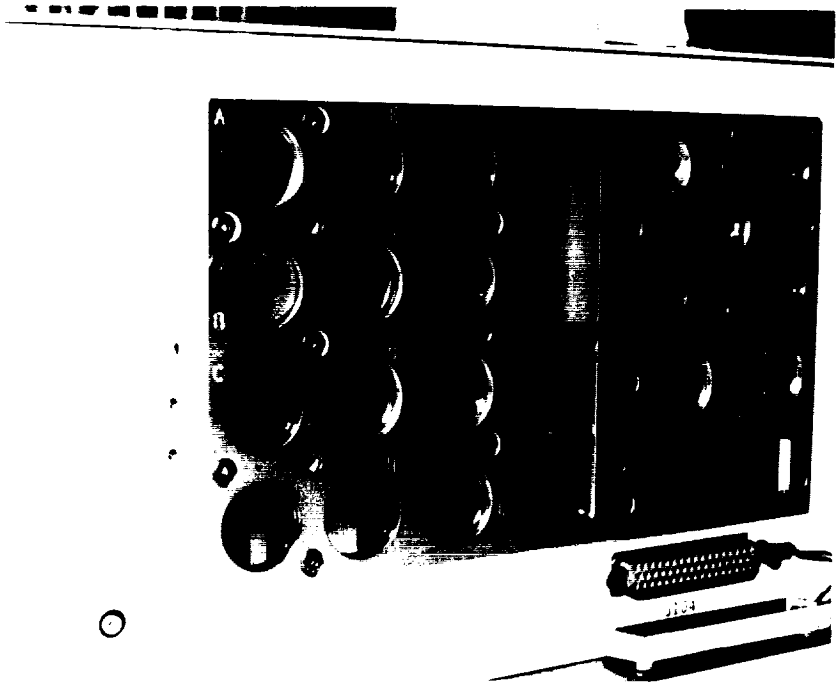

FIGURE 2. IOCM PASSIVE SAMPLE TRAY

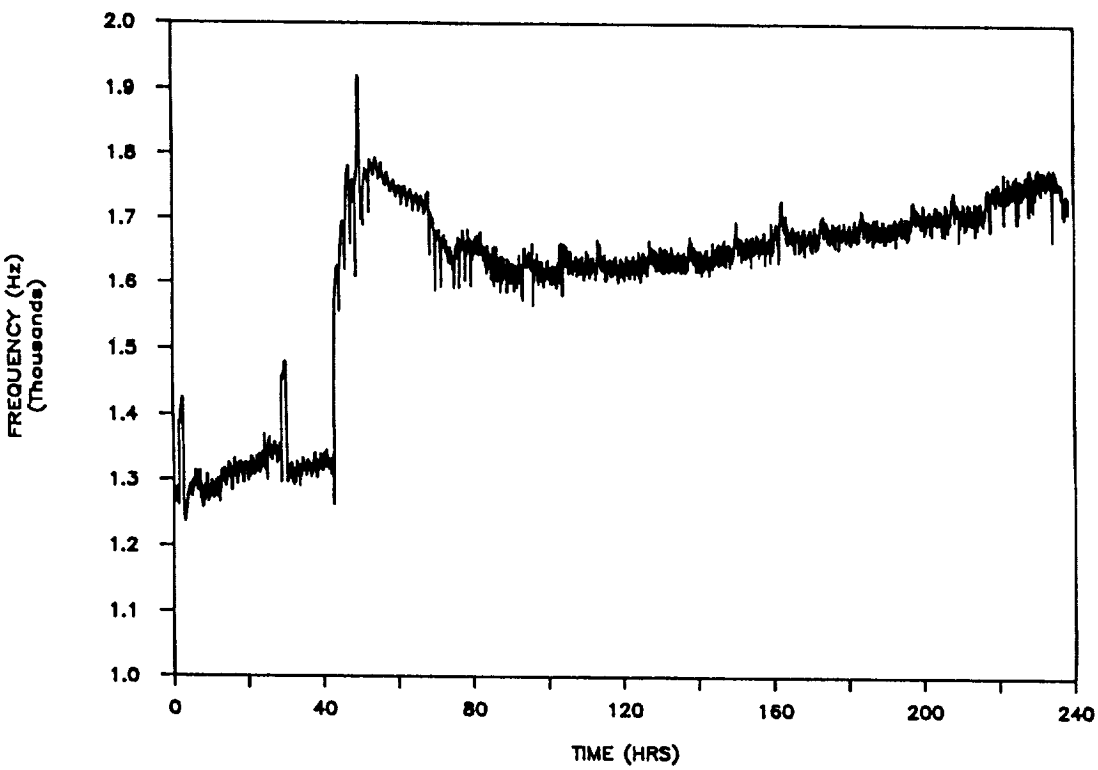

FIGURE 3. FREQUENCY CHANGE (MASS ACCUMULATION) OF TQCM 1; LAUNCH TO LANDING

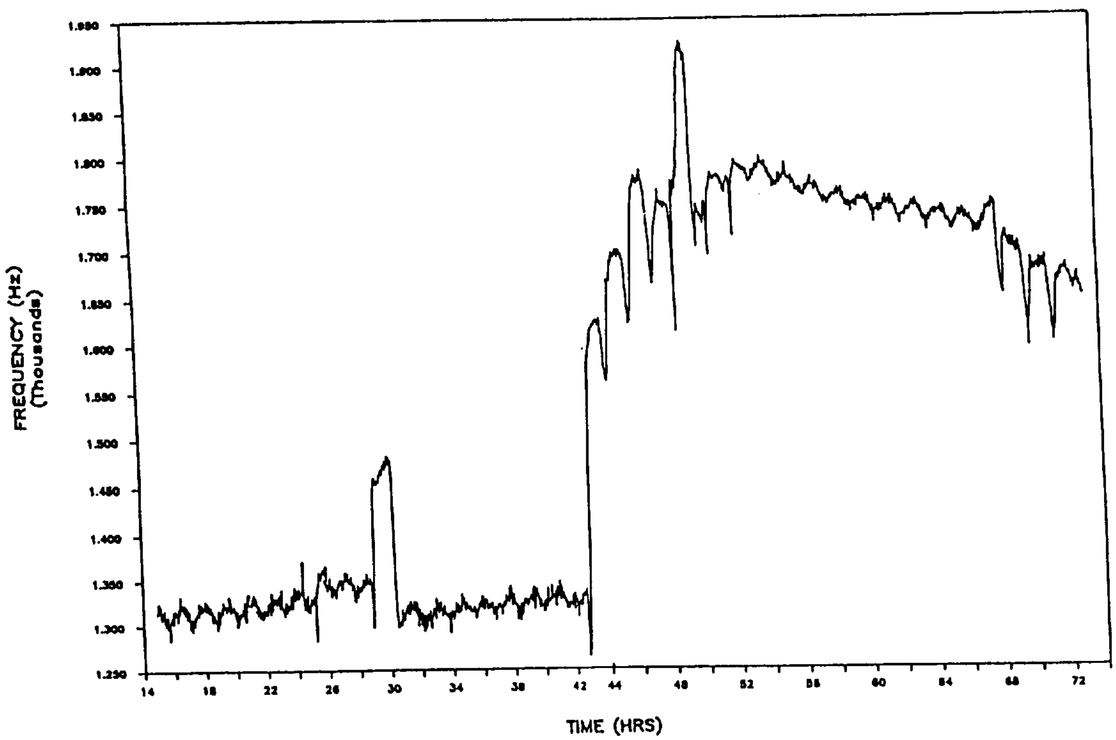

FIGURE 4. FREQUENCY CHANGE (MASS ACCUMULATION) OF TQCM 1; EARLY PHASE OF MISSION

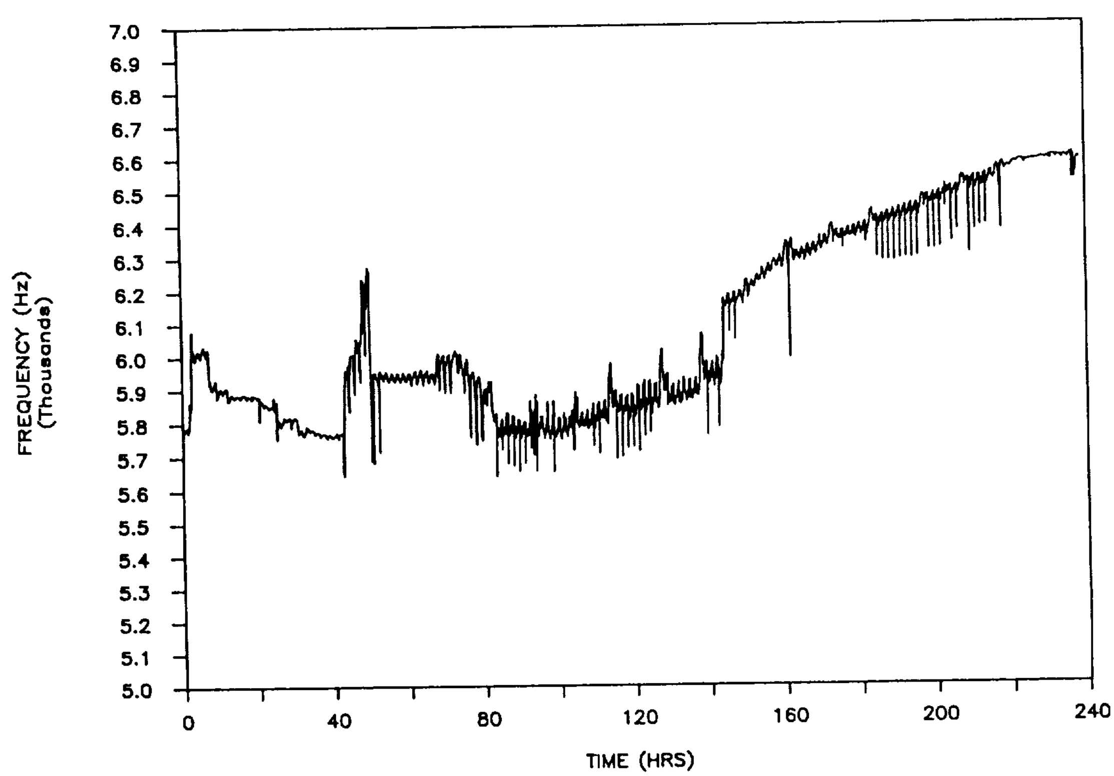

FIGURE 5. FREQUENCY CHANGE (MASS ACCUMULATION) OF TQCM 5; LAUNCH TO LANDING

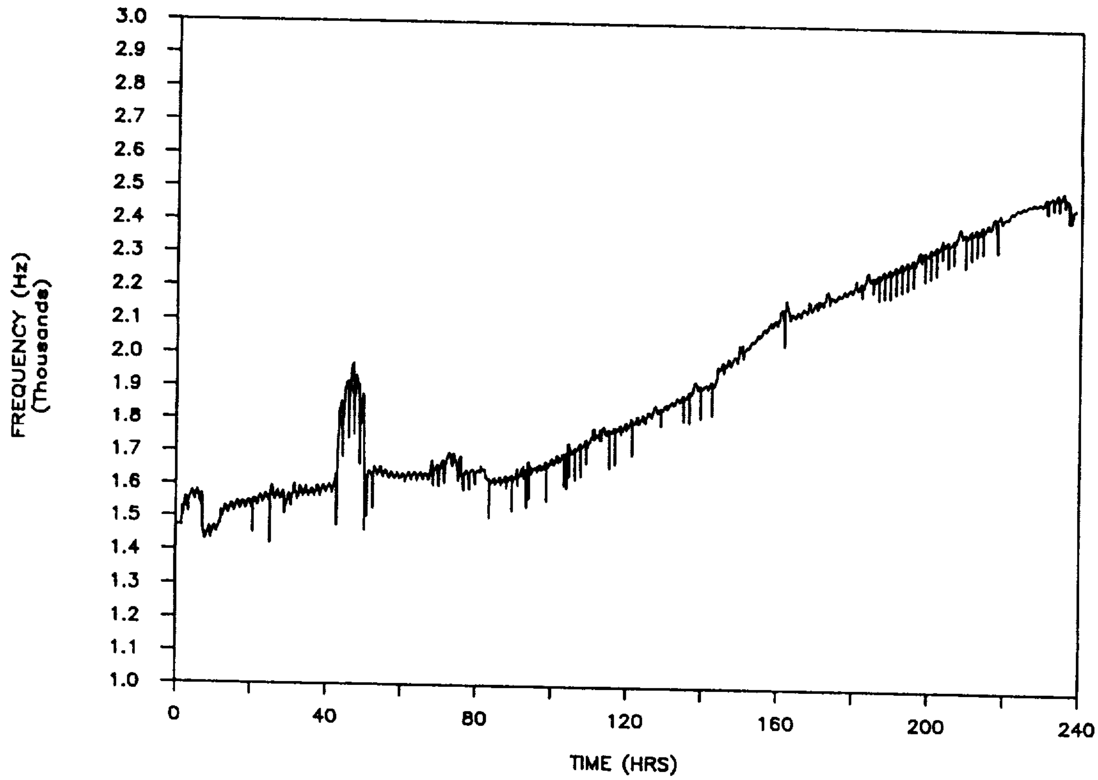

FIGURE 6. FREQUENCY CHANGE (MASS ACCUMULATION) OF TQCM 6; LAUNCH TO LANDING

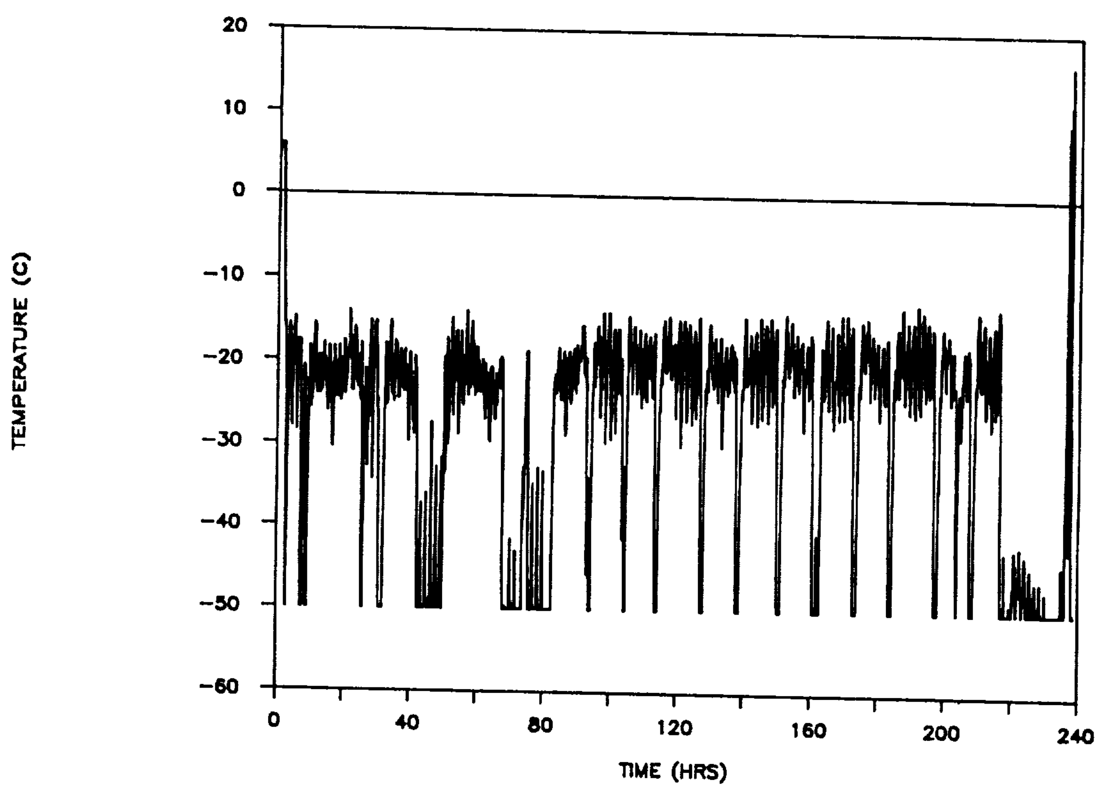

FIGURE 7. TEMPERATURE PROFILE OF THERMAL COATING CALORIMETER; LAUNCH TO LANDING

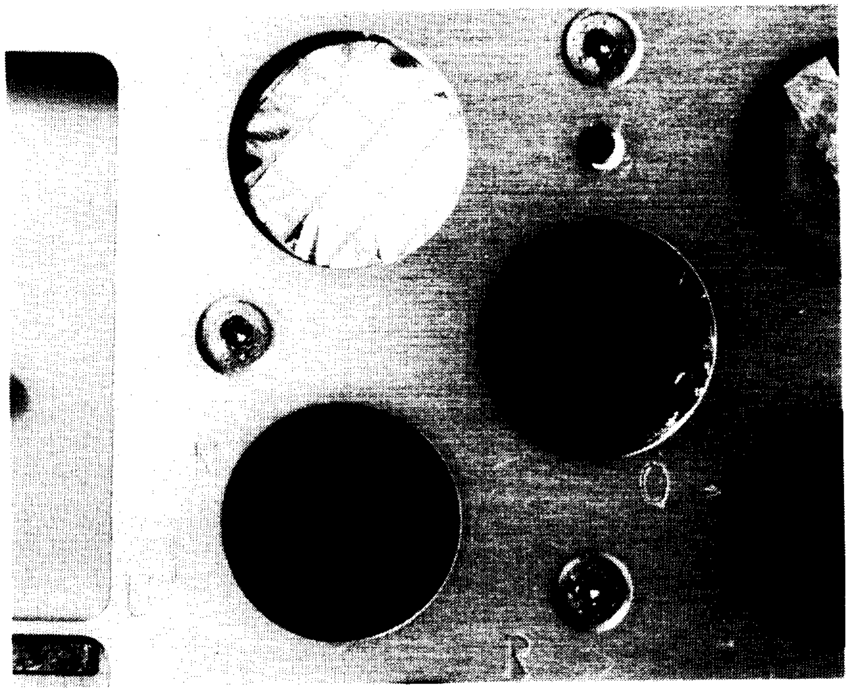

FIGURE 8. PASSIVE ARRAY IMPACT FILM

FIGURE 9. PERFORATION OF IMPACT FILM AND LDEF THERMAL BLANKET RESIDUE

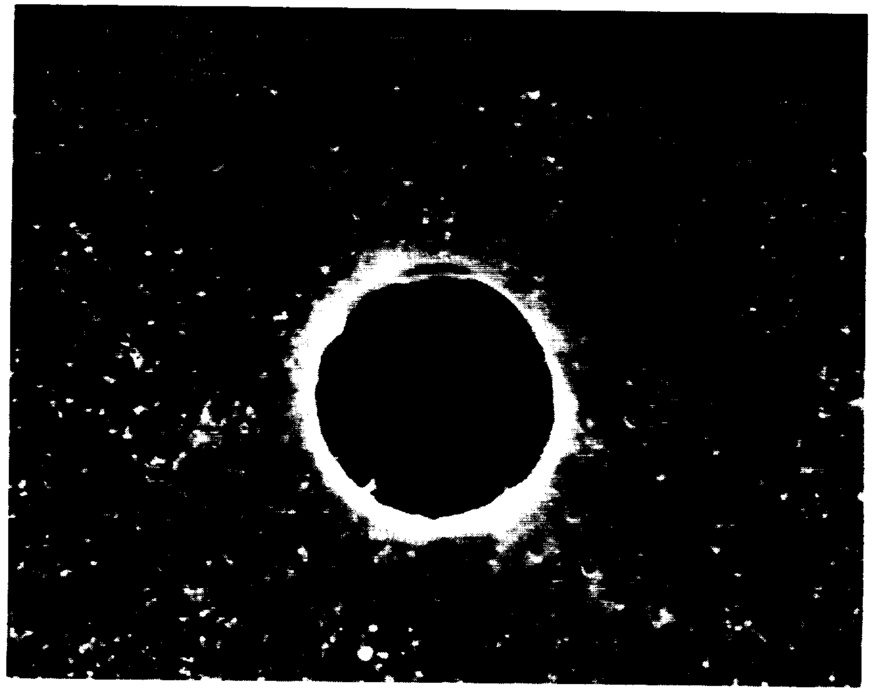

FIGURE 10. PERFORATION EVENTS IN IMPACT FILM

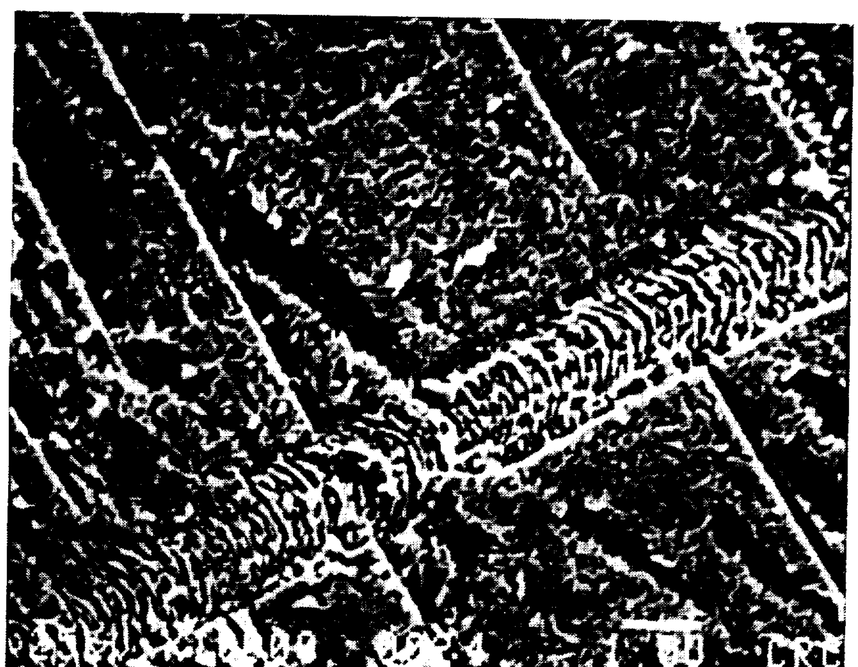

FIGURE 11. ONSET OF AO EROSION OF UNCOATED KAPTON

FIGURE 12. ONSET OF AO EROSION UNDER KAPTON PROTECTIVE COATING