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# RETURNED SOLAR MAX HARDWARE DEGRADATION STUDY RESULTS

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## ABSTRACT

The Solar Maximum Repair Mission returned with the replaced hardware that had been in low Earth orbit for over four years. The materials of this returned hardware gave the aerospace community an opportunity to study the realtime effects of atomic oxygen, solar radiation, impact particles, charged particle radiation, and molecular contamination. The results of 16 participants in these studies are summarized.

## INTRODUCTION

The Solar Maximum Mission (SMM) spacecraft, built at the Goddard Space Flight Center, was launched in February 1980 with solar flare research its primary objective. Launched near the peak of the 11-year solar cycle, the SMM was put in a 310 nm, nearly circular orbit with 28.5° inclination. The spacecraft's longitudinal axis was pointing at the Sun in a 3-axis stabilized mode, so that the seven instruments aboard the spacecraft could monitor the activities of the Sun. Some of the instruments required very fine pointing accuracy and stability to obtain high-resolution data. During the initial period, the pointing accuracy of the SMM was better than 2 arc-sec with stability less than 1 arc-sec.

The following instruments were carried by the SMM spacecraft:

- Active Cavity Radiometer Irradiance Monitor
- Coronagraph/Polarimeter (C/P)
- Gamma Ray Spectrometer
- Hard X-Ray Burst Spectrometer
- Hard X-Ray Imaging Spectrometer
- Ultraviolet Spectrometer/Polarimeter
- X-Ray Polychromator

Six of the instruments were designed to observe solar flares in regions of the electromagnetic spectrum ranging from visible light through ultraviolet and x-ray emission to gamma rays. The seventh instrument, the Active Cavity Radiometer Irradiance Monitor, monitored the Sun's total radiation.

### Equipment and Instrument Failures

The first months of the mission were very successful. The spacecraft and the instruments operated flawlessly with hundreds of flares monitored and recorded. In September 1980, about 6 1/2 months after launch, one of the three gyro channels (Channel C) of the NASA Inertial Reference Unit failed. The required attitude control was maintained, however, without performance degradation by the two remaining gyro channels (A and B) until November 1980, when three fuses burned out in the reaction wheel control circuits. In December 1980, a yaw magnetic torquer also failed. A coarse attitude control mode was established using the remaining magnetic torquers. The spacecraft was spin stabilized at a rotation rate of 1 deg/sec with a coning motion that moved the Sun pointing spacecraft axis up to 15° off the Sun line. Only two of the seven instruments were 100% operational (Gamma Ray Spectrometer and Hard X-Ray Burst Spectrometer) since they did not require precise pointing. One instrument functioned with limited capability (Active Cavity Radiometer Irradiance Monitor). Two of the instruments were not able to operate due to the backup attitude control mode (Ultraviolet Spectrometer/Polarimeter and X-Ray Polychromator) and two others had failed and were inoperative (Coronagraph/Polarimeter and Hard X-Ray Imaging Spectrometer).

## **Solar Maximum Repair Mission**

The Solar Max spacecraft was the first spacecraft designed to be serviced and repaired in space by the Space Shuttle crew. The Modular Attitude Control System (MACS) module was designed to be an orbital replacement unit, but the instrument repair was more complex because the Instrument Module (IM) was not designed to be repaired or replaced in orbit. Of the two failed scientific instruments, only the C/P was considered repairable. An identical spare MACS module was available from the Landsat program and a new C/P Main Electronics Box (MEB) was built specifically for the repair mission.

The Solar Maximum Repair Mission (SMRM) was performed by the crew of the STS flight 41-C in April 1984. By this time the SMM orbit altitude had decayed to 265 nm. Attempts by the astronaut using the Manned Maneuvering Unit (MMU) to dock to the spacecraft and to stop its rotation failed. The docking attempts imparted to the spacecraft uncontrollable roll, pitch and yaw rates. After the spacecraft was stabilized using specially uplinked software, the spacecraft was grappled by the Orbiter's Remote Manipulator System (RMS) and placed on the Flight Support System (FSS) located in the Orbiter Bay.

The MACS module was removed from the SMM and placed on its temporary storage fixture on the FSS. After the new module was mounted on the SMM, the old module was secured in its landing location on the lower starboard side of the FSS. The entire MACS module replacement took less than an hour.

The replacement of the Main Electronics Box of the Coronagraph/Polarimeter was the next repair operation. The MEB was replaced successfully, even though it was not designed for servicing. The faulty MEB was stowed in a storage area in the FSS tool locker for return to Earth.

After the replacement of the faulty equipment, the SMM was checked out and deployed to provide more data near the Sun's least active solar flare period. The Orbiter landed two days later on April 14, 1984.

## **Post-Flight Handling of Returned Equipment**

After landing at Edwards Air Force Base in California, the Orbiter and its returned payload were flown on the 747 to the Kennedy Space Center (KSC). After three days in the Orbiter Processing Facility (OPF), the FSS with MACS attached was removed from the Orbiter and transported to the Operations and Checkout (O&C) building.

Because of concern that contamination may mask the environmental effects on the returned equipment, the MACS and the MEB were bagged while in the O&C building and under QA control with rigid handling limitations. The MACS and MEB were removed from the FSS and placed in their respective storage containers. A one square foot wash plate and a fallout grid/surface had been attached to the MACS in the OPF before removal from the Orbiter to monitor molecular and particulate contaminants deposited from the time the MACS was taken out of the Orbiter bay to when it was unpacked at GSFC. The same procedure was used with MEB but the sequence started at the O&C building where the MEB was removed from the FSS tool locker.

Clean room attire was used by the handling personnel at all times. Except for the time when the units (MACS & MEB) were packed in their separate shipping containers, the units were protected from contamination by bagging made of Capran 518. When the wash plates and fallout plates were removed after unpacking the units at the GSFC, analyses indicated that the protected surfaces were in better condition than required by Mil Std 1246A level 100A.

The returned hardware was stored in a class 10,000 cleanroom at the GSFC. Thermal blankets were carefully cut and removed, then stored in display containers.

### **Post-Flight Analysis**

The returned MACS unit and the MEB of the Coronagraph/Polarimeter offered an opportunity to examine the hardware in an effort to determine the causes of the failures and to study the effects of 50 months exposure to the Low Earth Orbit (LEO) environment. Natural orbital environments, such as solar ultraviolet radiation, charge particles, atomic oxygen, and micrometeoroids have been demonstrated to degrade thermal radiative properties like solar absorptance, and material mechanical properties such as elongation and tensile strength. More subtle effects on surface electrical properties have also been observed. Similar effects can be caused by self-induced environments, such as molecular and particulate contamination and by space debris carried into orbit (or created) by the launch vehicle, the spacecraft, or the payload.

The atomic oxygen and space debris effects were for the most part noted from experiments on STS-3 to 8. The contrasts in effects should provide a gauge to assess the reliability of Orbiter based testing of materials for higher altitude and longer term predictions.

## **HARDWARE ANALYSES**

### **Main Electronic Box**

The Main Electronic Box (MEB) provides the control and data handling functions for the Coronagraph/Polarimeter (C/P) instrument. The coronagraph creates an artificial total eclipse of the Sun by using a series of external disks to prevent direct sunlight from falling on the objective lens of the telescope. The C/P operated successfully taking pictures of Sun's corona for 5 months after launch before the first failure occurred. Fortunately, the failed microcircuit could be bypassed by ground software. The second failure in the electronics occurred about a month later, August 8, 1980, but the instrument was kept operating with only an occasional loss of data. The third electronics failure occurred in early September, but a solution to prevent unnecessary shutdowns was found by modifying the onboard software. The terminal failure in the electronics occurred on September 23, 1980, which rendered the instrument inoperative.

Subsequent post-flight analysis showed that all the failures occurred in one type of integrated circuit MM54C161J/883B manufactured by National Semiconductor. There were a total of 21 such microcircuits in use of which three failed. Electrical testing of two of the devices isolated the failures to short circuited transistors. The third device could not be tested because of damage during removal from the PC board. The short circuits were caused by defects in the gate oxide material as a result of time, temperature and applied bias voltage. Several oxide defects were also observed in the third device.

In addition, nine National Semiconductor MM54C161J microcircuits were removed from the MEB and tested. All nine devices had been operating properly on the MEB. Two of the devices failed marginally the initial electrical tests. One device failed catastrophically a static burn-in test at 125°C for 24 hours. The failures were similar to the in-orbit failures of the parts of the same type. Also the parts had similar defects in the gate oxide material, which indicates a lot related problem. There is some question about the burn-in of these devices before delivery. A proper burn-in is an accepted determinant of a parts reliability and will usually weed out weak devices.

### **Radiation Effects of Selected MEB Electronic Parts**

A total of 29 parts of 9 different types were submitted to static, dynamic and functional electrical tests. The tested parts included flight parts and residual parts from the same date code lot as the original flight parts. The flight parts had been under power or bias for the first 8 months and about 10% of the time thereafter. These parts also had a year to anneal at ambient room temperatures on the ground.

The flight electronic parts showed no adverse effects due to the low Earth orbit radiation environment. Complex linear devices ( $\mu$ A108A) begin to degrade at low doses and dose rates and will be susceptible to failure at higher altitudes and/or longer exposures. More detailed evaluation of electronic parts in orbit will be possible from the CRRES mission planned for 1986 and from the Space Station. Radiation detectors will then actually measure the environment experienced by electronic parts which will be simultaneously monitored for electrical performance.

### **Selected Hardware Studies**

The evaluation was performed on the returned module retention system preload bolts, MEB honeycomb panel epoxy film adhesive and the thermal louver blade polyimide adhesive.

The two returned bolts were tested for yield strength and ultimate tensile strength. The tests showed no degradation in either category and the results were comparable to those of an unflown bolt.

The MEB honeycomb panel evaluation produced a conclusion that there was no degradation in room temperature bond strength of the epoxy film adhesive.

The returned louver polyimide blade adhesive was tested for lap shear strength and compared with unflown specimens. The results showed an average of 65% reduction in shear strength as compared to the unflown specimens. However, the reduction was not considered a severe one as evidenced by the bonding which survived the action and environments in good condition.

The returned thermal louver blades had red nodules on both sides of the blades. Evidence suggests that the red nodules represent regions of pure polyimide resin cured in space.

Infrared reflectometer measurements were performed on the returned louver blades and compared with those of unflown spare louver blades. The results showed no degradation of infrared reflectivity. Also the louver blade open and close temperature settings showed no degradation. The measured post-flight settings were well within the specification limits.

## **NASA Standard Inertial Reference Unit (DRIRU II)**

The returned unit was the first production DRIRU II (S/N 1001) used as one of the subsystems of the Modular Attitude Control System (MACS). The DRIRU is a self contained, strapdown, three axis, dual redundant attitude rate sensing unit. Three orthogonally mounted, two-degree-of-freedom gyros and a triplication of electronic modules and power supplies are used to provide full operational capability with any two of the three channels. The gyros in the DRIRU II are Teledyne SDG-5 Dynamically Tuned Gyros.

The investigation concluded that gyro channel C failed because of an intermittent electrical short in the motor control logic. Because the failure occurred near the South Atlantic Anomaly, much effort was devoted to determine if the failure could have been caused by radiation. After extensive tests, it was concluded that radiation was not a probable cause of the failure. Subsequent tests at the GSFC Parts Analysis Laboratory showed that the failures occurred in three logic devices. Two of the devices failed because of an electrical overstress. As of this date, the cause of the overstress has not been determined. The third device most likely failed because time, temperature, and an out-of-tolerance logic supply voltage created a short at a latent defect of the device. The defect apparently was caused by an irregularity in the manufacturing process. (See 'DRIRU II Electronics Parts Analysis.')

After the system was reassembled with two substitute electronic modules, a full series of tests were performed to evaluate the stability of the unit over the full operating temperature range. Also the repeatability of the parameters as compared to the delivered state was investigated. The test series were designed to repeat the complete 1978 acceptance tests.

The physical condition of the system was excellent with no apparent materials degradation. There was no evidence of system performance degradation due to operational and other environments. The system had excellent long-term stability of performance parameters over the launch, orbital operation and retrieval environments during a 74-month period.

There was no measurable degradation of the shock/vibration isolators as evidenced by the excellent alignment stability of the gyro axes through launch environments and over an extended time period.

There was no evidence of structural or mechanical changes and no apparent outgassing or degradation of exposed surfaces.

Examination at Teledyne found that the gyro ball bearings showed no excessive wear to raceways, balls, or retainers. However, there was some dark colored, viscous residue mainly in the ball tracks and the retainer ball pockets. (See 'DRIRU Bearings and Lubricant' for summary of GSFC analysis.)

### **DRIRU Bearings and Lubricant**

One of the DRIRU gyroscopes was disassembled and the bearings were returned to GSFC for examination. The gyroscopes had been running continuously in orbit for 4 years at 6000 RPM.

The bearings showed some wear in the form of tiny pits and scratch-line deformations. Numerous tiny particles were observed clinging to the bearing parts after the case and the hysteresis ring were removed. The particles had originated from the pits of the bearing races and the balls.

The lubricant for the bearings is contained in the retainers which are made from a porous, phenolic material. Examination showed that the bearings were lubricated.

The conclusion was that the bearings showed little wear and had a sufficient amount of lubricant left to perform without problems for their predicted life of 5 years.

### **DRIRU II Electronics Parts Analysis**

The failed part in the gyro channel C of the DRIRU II unit was an RCA CD4017AK microcircuit, a decade counter. The part was submitted to the GSFC Parts Analysis Laboratory for failure analysis. The tests determined that the failure was due to a short circuit through an oxide defect underneath the output metalization. The defect was the result of a manufacturing irregularity during processing.

Two other devices, an RCA CD4049AK and a CD4081BK, both microcircuits of the DRIRU II gyro motor control logic, were submitted to the GSFC Parts Analysis Laboratory for failure analysis. Both devices had failed in flight due to a fused open die metalization track. A pin on each of the devices was open circuited to all other pins. The fused open metalization was a result of electrical overstress.

### **Remote Interface Unit**

The Remote Interface Unit (RIU) was designed and built by the Fairchild Space Company. The first application of the RIU was on the SMM spacecraft. The unit provides two-way communications between electronic packages on the spacecraft and a central command and telemetry unit (CU) which decodes and distributes commands and generates telemetry formats. The CU communicates with the On-Board Computer (OBC) through the Standard Interface and with the ground via the RF equipment.

The standard MACS module carries two redundant RIU's which have three operational modes: 'OFF,' 'Standby 1,' and 'Standby 2.' The last two are sub-modes of the 'ON' mode. During the flight, Unit A was operating in the full 'ON' mode (Standby 2). Unit B was operating in the 'OFF' mode (only Bus Receiver/Control Logic and Power Converter continuously powered). Throughout the flight, no malfunctions of the Units were indicated.

The RIU's were returned to Earth with the MACS module and Unit B underwent a post-flight engineering evaluation from December 1984 until April 1985. The pre-flight tests were performed in 1979.

Post-flight external and internal visual inspection revealed no degradation. Besides the visual inspection, RIU B underwent two other kinds of engineering tests. Automated test equipment was used to qualify the unit as a whole ('GO - NO GO'). In the other test, a parametric test,



each parameter was evaluated separately. The parametric evaluation included user telemetry interface circuitry (active and passive analog linearity), phase lock loop performance, pulsed output current and width, serial digital commands, serial digital telemetry, and power dissipation.

The tests were performed at ambient temperature,  $-20^{\circ}\text{C}$ , and  $+60^{\circ}\text{C}$ . The cold and hot temperatures are the qualification limits. All parameters evaluated were found to be within specification. When compared to pre-flight test data, in many categories the post-flight data showed some improvement. The test results qualify the unit for reuse in another mission.

### **Three Axis Magnetometers**

Magnetometers are used to sense spacecraft attitude with respect to Earth's magnetic field. Two Three Axis Magnetometers, designated as the primary and secondary magnetometer, are part of the standard MACS module. The magnetometers are fluxgate magnetometers which produce three analog signals proportional to the magnetic field components along their input axes.

The magnetometers together with the magnetic torquers provided an important function during one part of the SMRM when they were used to stabilize the spacecraft's attitude. Only one of the magnetometers was used during the SMM. The other, serving as a backup unit, was never used because the primary unit did not malfunction.

After the magnetometers were returned to the manufacturer, they were subjected to the same performance tests which were performed before the flight. The post-flight tests showed that the magnetometers still satisfied the original specification requirements. The post-flight test data nearly duplicated the pre-flight data.

### **Standard Reaction Wheels**

The four Standard Reaction Wheels are components of the MACS module and are used for attitude control and stabilization. They are essentially flywheels and work on the principle of exchanging angular momentum with the spacecraft body. Normally, three of the wheels are aligned with the principal axes of the spacecraft. The fourth, a redundant skewed wheel, is used to replace any of the orthogonal wheels in case of a wheel failure. In normal operation it is run at a bias speed to keep the other three wheels away from zero speed and to maximize bearing life.

After the return of the wheels to the manufacturer on January 24, 1985, they were subjected to visual examination, preliminary electrical checks, performance tests at ambient, hot and cold temperature environments, and internal pressure measurements. One wheel, which showed a slightly deteriorated performance, was selected for teardown.

Visual examination found the wheels in good condition. Preliminary electrical tests, continuity, bonding, and isolation were satisfactory. The bonding resistance for two of the four units was slightly above the requirements but was not considered excessive.

The internal pressure measurements indicated that the pressures were far below atmospheric, confirming that the vacuum seal was still intact.

All four units successfully passed the performance tests with the exception of the 500 RPM torque noise test using a .1 rad/sec high pass filter. However, the units met the torque noise test with the 0.3 rad/sec high pass filter in the test circuit.

Individually, two of the units showed very similar performance results as compared to pre-flight tests. One unit showed decreased bearing drag torques and extended coastdown times. Another unit had a 45% increase in drag torques and reduced coastdown times, although it met all requirements. It had been exposed to a no-load overtemperature (60°C) for approximately 3 hours due to a software problem.

Teardown analysis of the overtemperature-exposed unit showed an 'as new' appearance of the internal components and surfaces. The lubrication analysis showed a greater lubrication loss in the floating cartridge system than in the fixed cartridge system. An investigation package including contamination wipes, lubricant samples, bearing components and photographs of some items was sent to NASA GSFC for analysis

### **NASA Standard Star Trackers**

The MACS module includes two Fixed Head Star Trackers (FHST) which are used together with the inertial reference unit and the on-board computer to determine and maintain the spacecraft's attitude with the required accuracy. Because the star tracker is a very sensitive instrument, its image dissector tube must be adequately protected from high level light sources such as the Sun. This was done by providing light shades and a shutter operated by a bright object sensor. At the time of the grappling attempt, the trackers and the shutter were powered-off. They remained in this condition until recovery.

The cathode of the image dissector tube detector was extensively damaged by the Sun following the attempts by the astronaut to dock with the spacecraft using the Manned Maneuvering Unit (MMU). The spacecraft was tumbling out of control for many hours before it was finally stabilized so that it could be grappled by the Remote Manipulator System. The tumbling exposed the sensitive cathode to the Sun causing permanent degradation. This prevented proper operation of the tracker after return to Earth and made comparison with pre-flight characteristics impossible. Otherwise, the tracker functioned nominally during testing at the GSFC and the Kennedy Space Center.

The trackers performed flawlessly during the Solar Maximum Mission. Because of inconsistencies in the flight data, some questions arose about the position calibration and alignment. The inconsistencies were attributed partly to a new calibration method and partly to the scarcity of flight data.

During the period from the spacecraft failure to just prior to recovery, the trackers were used occasionally, but were always adequately protected by the shutter.

The tests discovered that the 'tracks' made by the Sun across the cathode were insensitive regions which could not produce an adequate signal to track a star. It was also discovered that the lens of tracker S/N 001 had on its surface large peelings from the lens coating.

## MATERIALS ANALYSES

Materials analyses have been performed on materials retrieved from the Solar Max thermal control system, and on various impact particles that were imbedded in the thermal control materials. The materials analyzed were aluminized Kapton and Mylar, and Dacron netting from the multilayer insulation (MLI) blankets, and silver Teflon used on a thermal radiator and as trim on louver assemblies.

MLI is used to thermally insulate various spacecraft components. The portions of the MLI returned to Earth are primarily from the blankets used to insulate the MACS. Other pieces are from the blanket that covered the Main Electronics Box of the Coronagraph/Polarimeter. Aluminized Kapton is used for the top layer of the MLI. Other layers of the MLI are aluminized Kapton (MACS) or aluminized Mylar (MEB) separated by Dacron netting. A summary of the analyses is reported in the following section.

Silver Teflon is used on spacecraft components to increase the thermal radiation performance of exposed surfaces. The silver Teflon removed from the MACS is from the thermal louver assembly.

The chemistry of various impact particles, both natural and man made, has been analyzed. These impact particles were found imbedded in the MLI and in the thermal louvers. A summary of these analyses is reported in section 'Impact Particles.'

### **Insulation Materials**

There are two different forms of MLI insulation blankets returned to Earth from the Solar Max. In both forms, the top layer is made of Kapton with an aluminum layer vapor deposited on the inside surface. The bottom layer, the layer facing the spacecraft systems, is also made of aluminized Kapton, with the aluminum facing the inner layers of the MLI. In both forms, every layer is separated and supported by a Dacron mesh.

The MLI blankets that covered the MACS are composed entirely of aluminized Kapton. The top and bottom layers are made of 2 mil Kapton. There are six to ten inner layers of 1/4 mil Kapton, aluminized on both sides. The MLI taken from the Main Electronics Box is made of aluminized Kapton and aluminized Mylar. The top layer is 3 mil Kapton and the bottom layer is 1 mil Kapton. There are fifteen inner layers of 1/4 mil Mylar, aluminized on both sides.

The MLI materials have been analyzed by various investigators primarily using optical microscopes and Scanning Electron Microscopes (SEM). In addition, infrared spectroscopy was used to detect potential changes in the Kapton polymer structure, and a solar reflectometer measured solar absorptance. Measurements have been made of Kapton samples by exposing them to low pressure atomic oxygen discharge, to a microwave discharge rich in ultraviolet and to a 3 Kv argon ion beam under high vacuum conditions.

## Aluminized Kapton Degradation

The most apparent change in the MLI is the dull appearance of the top Kapton layers as compared to the shiny surface of new Kapton samples. Thus, studies of the MLI samples have concentrated on a possible degradation of the Kapton material. Observations show the outer Kapton surface to be eroded, thereby creating the dull appearance. This finding is similar to the results of tests performed on-orbit during the STS-8 mission. Findings on STS-8 as well as SMM indicate that changes in the Kapton are most likely due to the presence of atomic oxygen.

Degradation of the Kapton surface appears to be greater in areas cleaned during preflight operations with an alcohol based solvent. The same study has revealed tunnel-like substructures under the Kapton surface in the region of the interface between the alcohol wiped and non-wiped areas. It is believed that this is caused by the diffusion of atomic oxygen through the surface and reaction with the underlying polymers. Associated with the thin tunnel surfaces are small holes believed to be the result of atomic oxygen and UV interaction.

Infrared spectroscopy indicates that while there is obvious degradation in the Kapton, the actual polymer structure has not changed. Measurements of thickness of the top Kapton layer from the front of the MACS indicate that the Kapton suffered mass losses ranging from 0.54 percent to 31.4 percent. One sample from the bottom of the MACS suffered a 41 percent mass loss.

In order to more specifically determine the cause of the Kapton mass losses, Kapton samples were exposed to a variety of atomic oxygen sources, ion sources and ultraviolet (UV) sources. These tests suggest that the greatest surface etching is due to a combination of atomic oxygen coupled with exposure to UV. The angle at which the surface is exposed to these elements is probably significant.

Studies of the back side of the top Kapton layer from the MEB have revealed areas where the deposited aluminum is missing. These areas include scratches most likely caused by the handling of the MLI. Other areas are pinhole in size in a regular pattern, causing the illusion of penetrations in the transparent Kapton layer. These transparent pinholes appear to correspond with the knots in the underlying Dacron mesh, leading to the speculation that the knots have rubbed the aluminum off. While some surface holes appear to be the result of atomic oxygen and UV interaction or the illusion of transparent Kapton, other surface holes appear to be the result of particle impacts. Not all of these holes show a total penetration. The subject of particle impacts is discussed in section 'Impact Particles.'

The significance of the Kapton degradation to spacecraft designers lies in potential changes in the MLI performance. Measurements have been made of solar absorptance of the Kapton material. The solar absorptance of the Kapton material is typically 0.37 to 0.41 prior to on-orbit exposure. The post-flight measurements indicate that the solar absorptance of the SMM Kapton samples has increased by 0.03 to 0.04. This increase is probably due to the optical scattering effect of the degraded Kapton surface. This small increase should have little effect on the performance of the MLI insulation blankets. However, greater degradation of the top Kapton layer that may significantly affect the performance of the MLI, cannot be ruled out in future missions.

## **Inner Layer Material Degradation**

An examination has been made of the aluminized Mylar films and the Dacron mesh from the inner layers of the MLI which was used to cover the MEB. Optical microscopes of up to 400 power have revealed no erosion in these materials. The only apparent damage to these materials was caused by the impact particles (see 'Impact Particles').

## **Silver Teflon**

Silver Teflon is a thin Teflon film on which a layer of silver is vapor deposited. A layer of Inconel is deposited on the silver for protection from the environment. The Teflon film used on the SMM spacecraft is 5 mils thick with a 1500 Angstrom thick layer of silver and a 100 Angstrom thick layer of Inconel. Silver Teflon is used in the thermal protection system to increase the thermal radiative performance of various exposed surfaces. The film is normally applied so that the Teflon side is exposed to the orbit environment.

All silver Teflon samples given to investigators for analyses were exposed to the orbit environment on the Teflon side. Some material was also exposed on the silver/Inconel side, due to its unique application as trim on the MACS louver system (see 'Post-Flight Photographs'). It has been found in both cases that the surfaces were affected by the long duration exposure.

The silver Teflon has been analyzed, as in the case of aluminized Kapton, primarily with optical and Scanning Electron Microscopes. The absorptance of exposed samples has been measured and Energy Dispersive X-Ray Analysis (EDAX) has been used in conjunction with SEM to detect the presence of trace elements. Some samples have been tested with exposure to low pressure atomic oxygen discharge, and other samples have been subjected to tensile strength testing.

## **Teflon Surface Degradation**

Observations of Teflon exposed surfaces show evidence of a reaction to the orbit environment. Unexposed Teflon is smooth in appearance, while the exposed Teflon has been described as having a 'bristle-like' reaction pattern.

The bristle-like structures in exposed Teflon have also been described as cone-like structures. These adjacent cones are easily visible in magnified views of Teflon samples exposed to atomic oxygen and UV. The cause of this Teflon degradation has been studied by exposing a new sample of silver Teflon to atomic oxygen alone. Although the Teflon surface was no longer smooth, it did not have the deep cone structures of the SMM samples. There is speculation that a combination of atomic oxygen fluence and UV exposure will cause a more severe Teflon reaction than atomic oxygen alone, resulting in the cone structures.

Teflon is a fluorocarbon polymer. It has been found that exposure to atomic oxygen depletes Teflon of fluorine. This is evidenced by an increase in the detected carbon/fluorine ratio. Further study is required to determine if longer on-orbit exposures would result in any further breakdown of Teflon.

## Silver/Inconel Surface Degradation

The samples exposed on the silver/Inconel surface also show reaction to the orbit environment. Reactions range from cracks in the Inconel layer to a total depletion of silver and Inconel. In the later case, the exposed Teflon surfaces of some samples have developed the cone structures discussed earlier.

Many samples show the whole range of reactions. Between the extremes, a grain pattern of silver/Inconel was formed. Nearing the silver depleted regions, the grain bodies become smaller with the pattern of cracks more widespread.

The cracks in the Inconel surface may be due to temperature cycling under varying orbit conditions. Other evidence has indicated that the reaction of Inconel with atomic oxygen causes removal of the Inconel layer. Silver oxide deposits have been found on sample surfaces. The silver oxide may have come to the Inconel surface through the apparent cracks after the exposed silver reacted with atomic oxygen. Exposure tests indicate that the silver/Inconel depletion may be caused by exposure to atomic oxygen alone, or to a combination of atomic oxygen and UV. This suggests a mechanism for the loss of Inconel and silver. First, the atomic oxygen and temperature cycling causes the loss of Inconel and the formation of cracks. Silver oxide (and perhaps silver peroxide) forms and then flakes off in response to temperature cycling. This cycle continues until Teflon is exposed, and the Teflon reacts to atomic oxygen and UV resulting in the formation of the cone structures.

Tensile strength tests have shown that samples with eroded surfaces have no resilience. Abrupt breaks appear to have occurred in the same direction as thermal expansion/contraction. It was found that the tensile modulus of silver Teflon exposed to atomic oxygen decreased by about 15%, while the modulus of samples exposed to atomic oxygen and UV decreased by about 30%.

Measurements have been made of solar absorptance of the returned Teflon material. The solar absorptance of the Teflon film is typically 0.05 to 0.07 prior to on-orbit exposure. The Teflon samples having the greatest absorptance change, appear to be those exposed to the orbit environment on both sides of the film, and those contaminated by spacecraft outgassing. In these samples, the solar absorptance has increased by as much as 0.22 to 0.29. This large change in absorptance indicates a potentially large change in the performance of the Teflon film. The solar absorptance of Teflon film samples with non-eroded silver/Inconel surfaces had increased by a maximum of 0.04.

## Impact Particles

A survey of approximately one-half square meter of MLI has revealed over 1500 impact sites. Of these, 432 impacts resulted in craters in the Kapton greater than 40 microns in diameter. In the 75-micron thick Kapton (MEB), craters greater than 100 microns in diameter are

perforations through the Kapton layer. In the 50 micron Kapton (MACS), craters larger than 70 microns in diameter penetrate through the Kapton. When the survey totalled approximately 0.7 square meters of Kapton surface, about 160 impact craters penetrating the Kapton layer were found.

A number of particles completely penetrated all of the MLI layers. One particle penetrated the MLI near a star tracker, making an impression in the star tracker's aluminum shield. Approximately half of the particles that impacted the MACS louvers penetrated the first of the two aluminum sheets, as evidenced by impressions in the second sheet.

Chemical analyses of a number of the impacts has shown that sources of the particles fall into one of four groups. The first group of particles is meteoric material, evidenced by the elements silicon, magnesium, iron, calcium, aluminum with minor amounts of iron-nickel sulfide. The second group of particles is paint particles. This is characterized by titanium and zinc, and the chemistry includes potassium, silicon, aluminum and chlorine. The third group of particles is aluminum droplets, probably from the MLI. The fourth group of particles is waste particles as evidenced by one impact that penetrated three layers of MLI. The chemistry includes sodium, potassium chlorine, phosphorus and minor amounts of sulfur. Investigators believe that this particle may have come from the Orbiter's waste management system.

Two of the large impacts have been investigated in more detail. In both cases, the impact particle apparently disrupted upon impact with the outer Kapton layer of the MLI. The disrupted material was sprayed inward in a cone shaped pattern, lodging on the second layer of the MLI.

In the case of the first impact particle, a small portion of disrupted material penetrated the second layer of the MLI. This impact particle caused a hole 280 microns in diameter with a raised rim. The second MLI layer has a ring of tiny holes and craters surrounding a roughed up area of about 5 millimeters in diameter. Particles from the back of the first layer and from the front of the second layer have been analyzed showing that about 75% are fragments or melted droplets of Kapton. Of the non-Kapton particles, most are composed of magnesium, silicon and iron. Next in number were aluminum particles. Investigators believe that the aluminum is derived from the MLI. Other particles are composed of iron, sulfur and nickel.

The second reported impact particle caused a crater 355 microns in diameter with a raised rim in the Kapton layer. The second layer has a wedge shaped pattern of concentric, elongated holes. Particles of the second impact are composed primarily of iron, sulfur and nickel.

## INTRODUCTION

SMM FLEW FOUR YEARS IN LEO PRIOR TO REPAIR

- LAUNCHED TO 310 NM
- REPAIRED AT 265 NM

SMRM RESULTED IN THE RETURN OF:

- ATTITUDE CONTROL SUBSYSTEM MODULE
- CORONOGRAPH/POLARIMETER MAIN ELECTRONICS BOX

THIS PRESENTATION DESCRIBES FLIGHT HISTORY, OBSERVATORY ELEMENTS AND ATTITUDES, RECOVERED HARDWARE, AND STUDIES PERFORMED ON THE RETURNED HARDWARE, ELECTRONICS, AND THERMAL MATERIALS

## SMM FLIGHT HISTORY

LAUNCH TO 310 N.M.

FEBRUARY 1980

3-AXIS STABILIZED  
SUN-POINTING

ATTITUDE CONTROL FAILURE

NOVEMBER 1980

WOBBLE UP TO 15° OFF SUN  
ROTATING AT 1°/SEC

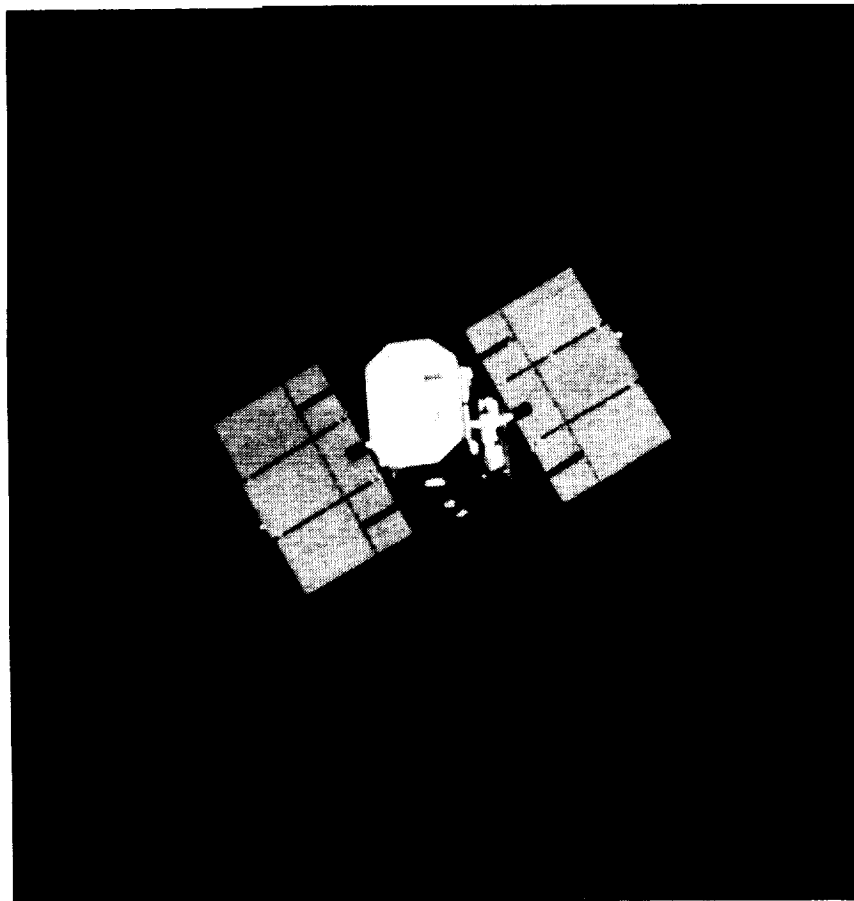
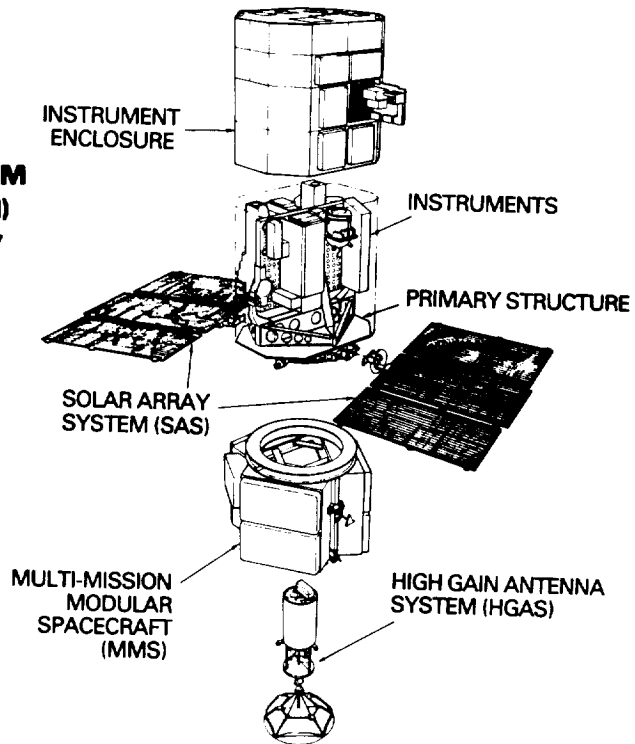
SMM REPAIR AT 265 N.M.

APRIL 1984

ACS, MEB RETURNED

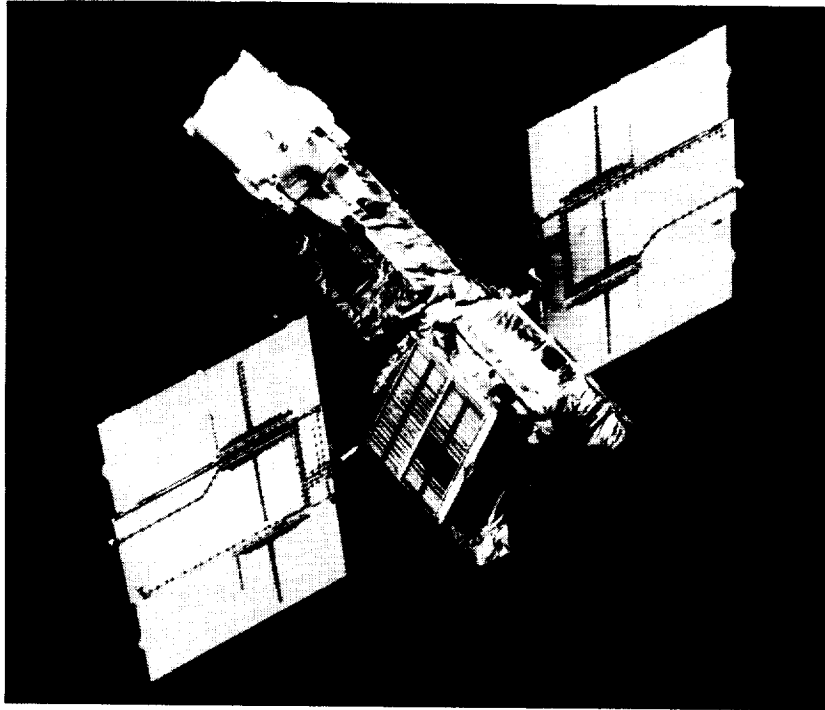


**SOLAR MAXIMUM  
MISSION (SMM)  
OBSERVATORY**



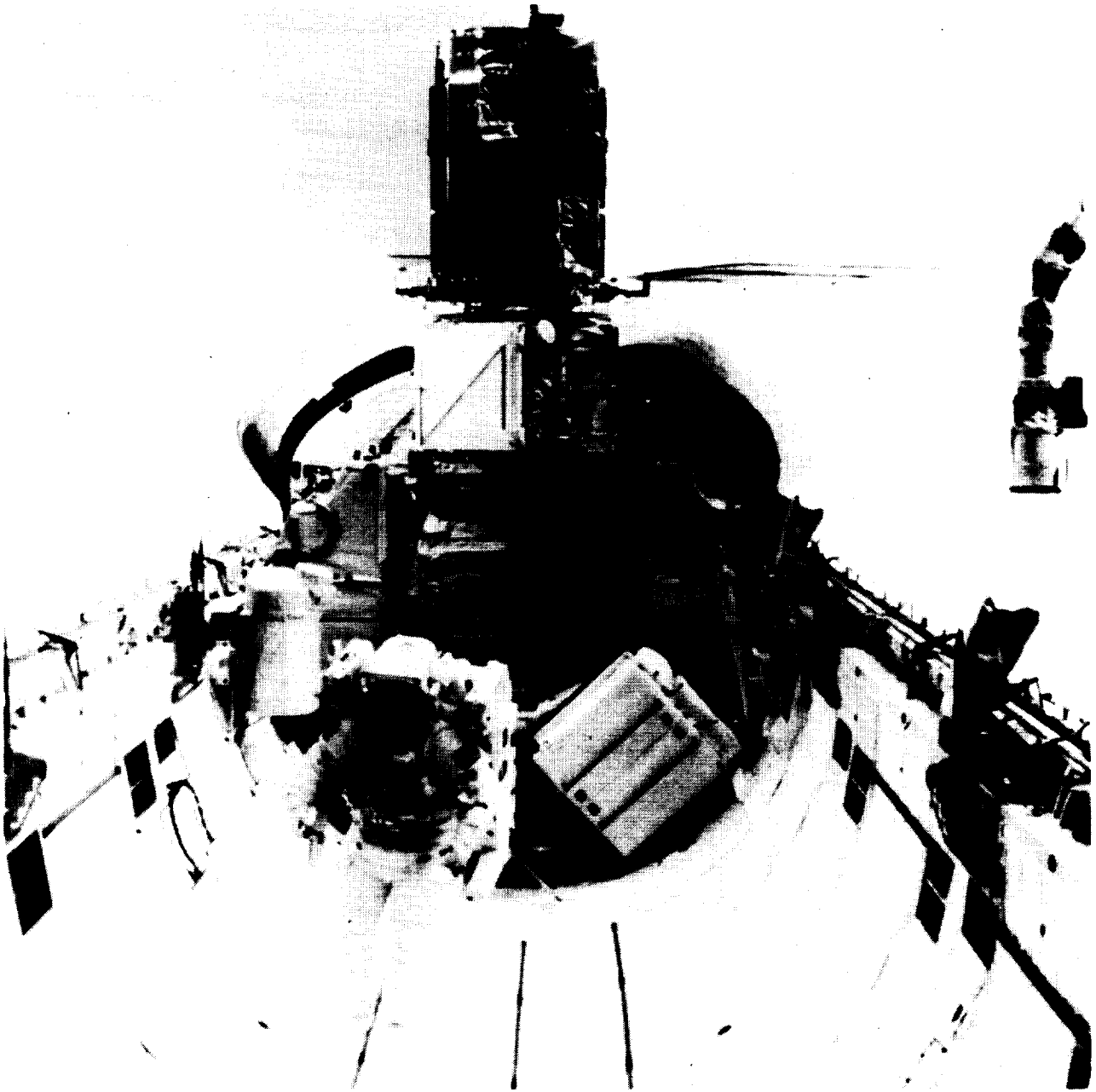
SMM as seen by the Sun in the post-failure attitude (15° wobble).

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View of MACS module after unsuccessful dock attempt. Most louvers are closed. Degradation of the bottom-facing trim (Teflon) can be seen.

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SMM in-bay after repairs completed.

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## DEGRADATION STUDY WORKSHOP CHRONOLOGY

MAY 1984: ISSUED INVITATION ON ALL AEROSPACE COMPANIES,  
NASA CENTERS, DOD ORGANIZATIONS AND UNIVERSITIES

JUNE 1984: FIRST WORKSHOP MEETING WITH INTERESTED  
PARTICIPANTS  
- RESEARCH TASKS PROPOSED AND DISCUSSED  
- RESPONSIBILITIES ASSIGNED  
- BEGAN DISTRIBUTION OF MATERIAL AND HARDWARE

JULY 1984 TO  
APRIL 1985: RESEARCH INVESTIGATIONS CARRIED OUT BY WORKSHOP  
PARTICIPANTS

MAY 1985: STUDY RESULTS PRESENTED BY PARTICIPANTS AT GSEC

JUNE/JULY 1985: FINAL DETAILED REPORT SUBMITTED BY EACH  
PARTICIPANT

## SMRM STUDIES SUMMARY

### SURFACE MATERIAL STUDIES

<u>PRINCIPAL INVESTIGATOR</u>	<u>ORGANIZATION</u>	<u>SUBJECT</u>
W. STUCKEY	AEROSPACE	TEFLON ANALYSIS
R. FRISTROM	APPLIED PHYSICS LAB	KAPTON OXYGEN EROSION AND OTHER SURFACE EFFECTS
R. LIANG	JPL	TEFLON BULK PROPERTY DEGRADATION BY OXYGEN
A. WHITAKER	MSFC	KAPTON EROSION RATES AND MECHANISMS
M. MCCARGO	LOCKHEED	TEFLON, KAPTON SURFACE AND BULK EFFECTS
B. SANTOS	LANGLEY	TEFLON, KAPTON SURFACE CHEMISTRY, THERMAL EFFECTS
D. KESSLER	JSC	BLANKETS, LOUVERS SPACE PARTICLE IMPACTS
J. PARK	GSEC	TEFLON, KAPTON, CONTAMINATION

SMRM STUDIES SUMMARY

PARTS COMPONENTS HARDWARE

<u>PRINCIPAL INVESTIGATOR</u>	<u>ORGANIZATION</u>	<u>SUBJECT</u>
C. UPTON	SHONSTEDT	MAGNETOMETER ELECTRICAL AND MAGNETIC PERFORMANCE
H. FRANKEL	FAIRCHILD	RIU ELECTRICAL; MEM; HONEYCOMB, LOUVERS MECHANICAL
J. RITTER	TELEDYNE	DRIRU ELECTRICAL, MECHANICAL PERFORMANCE
J. UBER	GSEC - METALLURGY	DRIRU BEARING WEAR AND OIL DEGRADATION
R. LEE	GSEC/HAO	MEB BOX FAILURE ANALYSIS
A. ANSTEAD	GSEC - PARTS	DRIRU AND MEB PARTS MICROSCOPIC ANALYSIS
R. MAURER	APL	COMPARISON OF IRRADIATED "NEW" PARTS TO FLOWN PARTS
C. SUTTER	SPERRY	WHEEL TORQUE AND POWER STUDIES; MEASURE LUBRICANT LOSS
P. NEWMAN	GSEC - ACS	STAR TRACKER SENSITIVITY AND ELECTRICAL PERFORMANCE

VERIFICATION OF IN-FLIGHT ANOMALIES

POST-LANDING ACS FUNCTIONAL TEST

- DETECTED OPEN FUSE ON 28V SUPPLY TO DRIRU CHANNEL C
- OBSERVED SYMPTOMS OF FUSE FAILURE THAT DISABLE REACTION WHEELS

C/P MEB - BAD LOT OF NATIONAL MM54C161 MICROCIRCUITS

- 21 OF THESE PARTS IN MEB, OF WHICH 3 FAILED ON-ORBIT
- DEFECTS IN GATE OXIDE MATERIAL CAUSED TRANSISTOR SHORTS

DRIRU CHANNEL C FAILURE ANALYSIS

- MANUFACTURING DEFECT CAUSED SHORT IN A RCA MICROCIRCUIT
- ELECTRICAL OVERSTRESS CAUSED FAILURE OF TWO OTHER RCA PARTS

### OTHER ELECTRONIC BOXES

ACS MAGNETOMETER AND REMOTE INTERFACE UNIT SHOWED NO ELECTRICAL DEGRADATION

DRIRU CHANNELS A & B HAD NO SIGNIFICANT CHANGES IN MECHANICAL OR ELECTRICAL PERFORMANCE

STAR TRACKER ELECTRONICS HAD NO CHANGES IN PERFORMANCE DETECTOR CATHODES DAMAGED DURING REPAIR MISSION

### RADIATION EFFECTS ON PARTS

DYNAMIC AND FUNCTIONAL TESTS PERFORMED ON 27 PARTS OF 7 DIFFERENT TYPES

- COMPARISON OF FLOWN PARTS TO RESIDUAL INVENTORY
- SOME RESIDUAL PARTS WERE IRRADIATED AND RETESTED

NO ADVERSE EFFECTS FOUND ON 6 PART TYPES, INCLUDING CMOS

COMPLEX LINEAR DEVICE (LM 108 OP AMP) SHOWED SLIGHT RADIATION DEGRADATION

- WOULD BE SUSCEPTIBLE TO FAILURE AT HIGHER DOSES

### BEARING AND LUBRICATED COMPONENTS

DRIRU BEARING SHOWED MINIMAL WEAR AFTER TEN BILLION REVOLUTIONS

- SOME SCRATCHES AND FINE METAL PARTICLES
- GYRO MECHANICAL PERFORMANCE SHOWED NO DEGRADATION

ALL FOUR REACTION WHEELS REMAINED WITHIN SPEC

- THREE WHEELS SHOWED NO DEGRADATION IN DRAG TORQUE

ROLL-AXIS WHEEL DRAG TORQUE INCREASED BY 45 PERCENT

- HAD EXPERIENCED TEMPERATURE > 60°C DURING FLIGHT
- DISASSEMBLY SHOWED 10 PERCENT LUBE LOSS AFTER 4 YEARS IN SPACE

## DEGRADATION OF MECHANICAL PROPERTIES

MODULE PRELOAD BOLTS HAD NO CHANGE IN REMOVAL TORQUE  
- NO DEGRADATION IN YIELD OR ULTIMATE STRENGTH

MEB HONEYCOMB PANEL ADHESIVE BOND STRENGTH WAS UNCHANGED

ACS LOUVERS SHOWED NO CHANGES IN ACTUATION TEMPERATURES

## SPACE PARTICLE IMPACTS

1500 PARTICLE IMPACTS FOUND IN 1/2 M<sup>2</sup> OF BLANKET  
- 10 PERCENT OF PARTICLES PENETRATED ONE LAYER OF KAPTON

SPACE DEBRIS IMPACTS OUTNUMBERED MICROMETEORIDS BY 2 TO 1  
- PAINT PARTICLES, ALUMINUM, WASTE PARTICLE  
- ONE PARTICLE PENETRATED 17-LAYER BLANKET

ALUMINUM LOUVER BLADES (1M<sup>2</sup>) HAD 64 PENETRATIONS  
- NO PARTICLES PENETRATED BACK SIDE OF BLADE

JSC SPONSORED CONSORTIUM HAS BEEN STUDYING REMAINDER OF MATERIAL

## OXYGEN/UV EFFECTS ON THERMAL SURFACES

KAPTON MASS LOSS SIMILAR TO STS EXPERIENCE  
- EROSION PATTERN MUCH SMOOTHER  
- MATERIAL STRENGTH UNAFFECTED  
- SOLAR ABSORPTANCE INCREASE BY 10%

REACTIONS OF UNSUPPORTED SILVER TEFLON  
- THERMAL CYCLING CAUSED CRACKS IN SILVER LAYER  
- NEGLIGIBLE EFFECT ON THERMAL PROPERTIES WHEN SILVER IS NOT EXPOSED  
- SILVER WAS REMOVED BY OXYGEN REACTION WHEN EXPOSED

TEFLON SIDE ALSO EXPERIENCED SOME EROSION  
- MUCH MORE EROSION WHEN EXPOSED TO UV  
- SOME EROSION DUE TO REACTION OF HYDROCARBON IMPURITY



Close up of the degraded silver Teflon louver trim on the "bottom" side to solar radiation and the atomic oxygen fluence on the silver/Inconel side of the silver Teflon.

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SELF-INDUCED CONTAMINATION

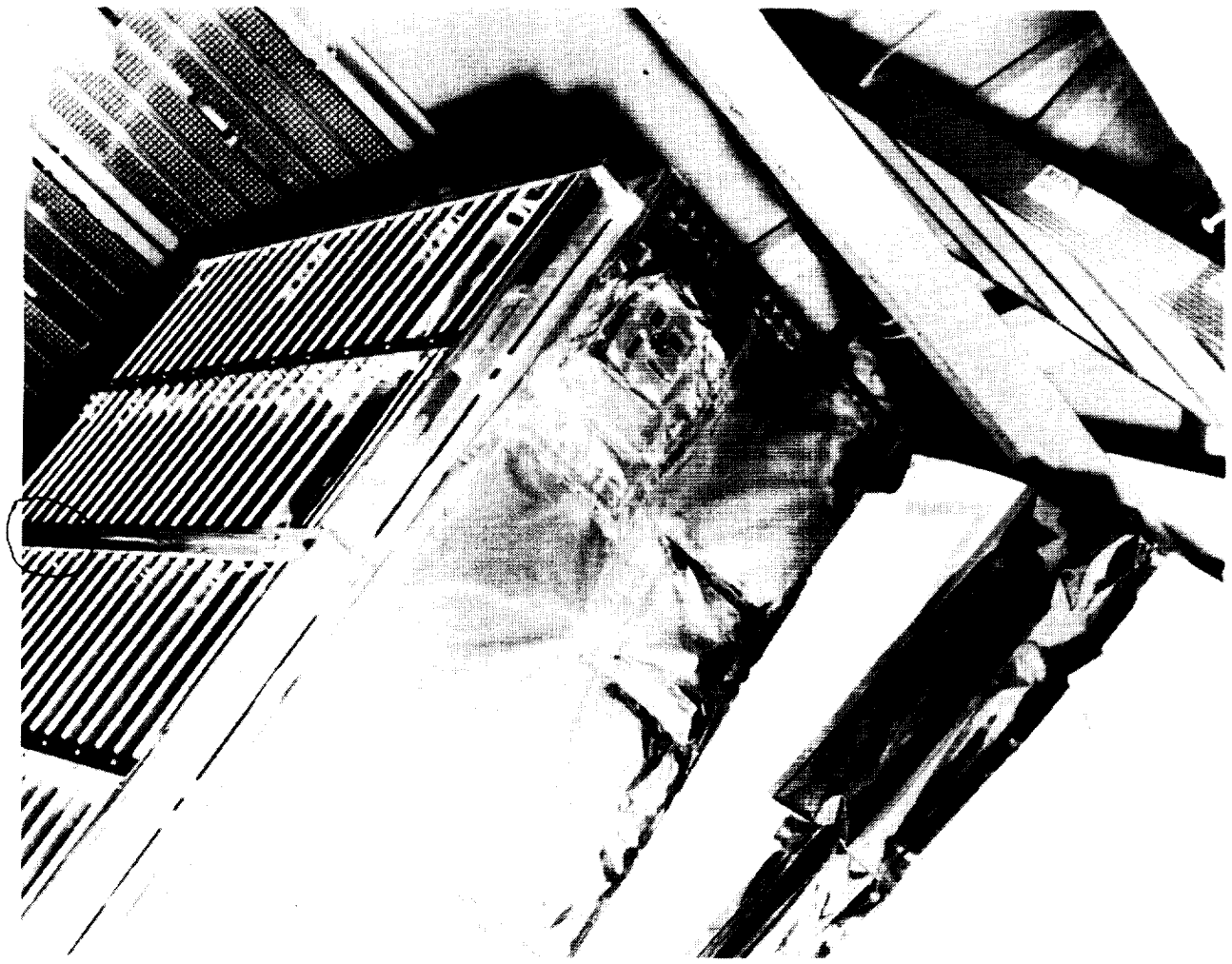
ACS MODULE SAW FOUR THERMAL VAC CYCLES AT MODULE QUALIFICATION  
- TEMPERATURE 100C MORE EXTREME THAN FLIGHT

WHITE SUBSTANCE ON FINE SUN SENSOR, COMPOSITION UNKNOWN  
- CONDENSED ON COLD SURFACE FROM WARM INTERIOR OF MODULE

SILICA BASED RESIDUE ON LOUVER FRAME NEAR MODULE VENT  
- OUTGASSING DEPOSIT FROM OIL, THERMAL GREASE, STAKING, ETC.  
- SIMILAR CONDENSATE AROUND VENT BETWEEN STAR TRACKERS



White powder residue from unintentional vent on sun sensor radiator.



Silica based residue (circled) on louver frame.

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## CONCLUSION

IN-FLIGHT ANOMALIES WERE VERIFIED: OTHER ELECTRONICS BOXES DID NOT DEGRADE

RADIATION DEGRADATION WAS DISCOVERED IN ONE PART TYPE

GYRO AND WHEEL BEARINGS IN GOOD SHAPE

THE EFFECT OF SPACE PARTICLE IMPACTS MUST BE CONSIDERED IN DESIGN OF FUTURE SPACECRAFT

EXPERIENCE INDICATED A NEED FOR AWARENESS OF UNINTENTIONAL VENTING IN CONTAMINATION CONTROL DESIGN CONSIDERATIONS

COMPARISON OF SMM AND STS RESULTS DEMONSTRATED VALIDITY AND LIMITATIONS OF PREDICTING LONG-TERM LEO EFFECTS FROM STS BASED STUDIES