N92-23287

MIGRATION AND GENERATION OF CONTAMINANTS FROM LAUNCH THROUGH RECOVERY: LDEF CASE HISTORY*

E. R. Crutcher, L. S. Nishimura, K. J. Warner, and W. W. Wascher
Boeing Defense and Space Group
Seattle,WA 98124-2499
Phone: 206/773-7002, Fax: 206/773-1473

SUMMARY

When LDEF entered orbit its cleanliness was approximately a MIL-STD-1246B Level 2000C. Its burden of contaminants included particles from every part of its history including a relatively small contribution from the shuttle bay itself. Although this satellite was far from what is normally considered clean in the aerospace industry,contaminating events in orbit and from processing after recovery were easily detected. The molecular contaminants carried into orbit were dwarfed by the heavy deposition of UV polymerized films from outgassing urethane paints and silicone based materials. Impacts by relatively small objects in orbit could create particulate contaminants that easily dominated the particle counts within a centimeter of the impact site.

During the recovery activities LDEF was 'sprayed' with a liquid high in organics and water soluble salts. With reentry turbulence, vibration, and gravitational loading particulate contaminants were redistributed about LDEF and the shuttle bay. Atomic oxygen weakened materials were particularly susceptible to these forces. The ferry flight exposed LDEF to the same forces and again redistributed contaminants throughout the bay.

Once in SAEF-2 there was a steady accumulation of particulate contaminants. These included skin flakes, paper fiber, wear metals, sawdust, and pollen to name a few. Some surfaces had a tenfold increase in their particle loading during their stay in SAEF-2. A few of the cleaner surfaces experienced a hundredfold increase.

It was possible to recreate the contamination history of LDEF through an analysis of its contaminants and selective samples that were collected from surfaces with better documented exposure histories. This data was then used to compare estimates based on monitoring methods that had been selected for the purpose of tracking LDEF's exposure to contaminants. LDEF experienced much more contamination than would have been assumed based on the monitors.

Work is still in progress but much of what has been learned so far is already being used in the selection of materials and in the design of systems for space. New experiments are being prepared for flight to resolve questions created by the discoveries on LDEF. This paper is a summary of what has been learned about LDEF contaminants over the first year since recovery and deintegration. Over thirty-five specific conclusions in five contamination related categories are listed at the end of this paper. Much more information will be available with further study.

*Work done under NAS 1-18224, Task 12

INTRODUCTION

The Long Duration Exposure Facility (LDEF) satellite has had a complex history of exposure to contaminants and exotic environments as illustrated in Figure 1. Prior to launch (Fig. 1, position 1) LDEF had on its surfaces an extraordinary variety of contaminants collected during all phases of preparation, including cleaning activities. During its launch (Fig. 1, position 2) in April of 1984 aboard the space shuttle Columbia it accumulated additional contaminants from the shuttle bay. Once in low earth orbit at an altitude of approximately 280 nautical miles (Fig. 1, position 3) hydrocarbon and silicone components, paints, adhesives, and contaminant films began outgassing or offgassing into the local LDEF environment. Much of this material condensed on surfaces of the satellite exposed to ultraviolet light and became a stable surface film modifying the optical and thermal properties of that surface. LDEF also began accumulating micrometeorites and space debris as it swept through space. These energetic impacts redistributed fragments, droplets, or condensates of LDEF materials. The high energy ultraviolet light of low earth orbit also began modifying surface carbon based materials creating new outgassing species. Initially low levels of atomic oxygen slowly interacted with the ram facing surfaces of the satellite. As its orbit decayed the flux of atomic oxygen increased,burning away hydrocarbon films and converting silicones into inert silicates. In January of 1990 the crew of the space shuttle Columbia grappled LDEF in orbit (Fig. 1, position 4) and gently moved the satellite into its cradle in the bay. As gentle as it was the grappling released clouds of small particles along with a few solar cells and other large objects. Again nested in the shuttle bay the satellite was brought back into the rich gaseous environment of this planet's surface (Fig. 1, position 5 and 6). Turbulent flow over the surface of the shuttle bay and LDEF during this return redistributed and mixed contaminants from both surfaces. LDEF's contribution to this mix significantly exceeded that from the shuttle bay but the contribution of new particles to the surface of LDEF was evident. The ferry flight exposed LDEF to another variety of environments and again to turbulent flow (Fig. 1, position 7 and 8). At some time during its recovery LDEF was sprayed with an aerosol of fine droplets of a hydrocarbon containing material (Ref. 1). Finally at Kennedy Space Center the satellite was removed from the shuttle bay (Fig. 1, position 9) and transported to the SAEF-2 clean room (Fig. 1, position 10). The contamination in the shuttle bay was monitored from before the launch of the Columbia through the removal of LDEF from the shuttle bay by the IOCM experiment package.

In the SAEF-2 clean room LDEF continued to interact with its new gas rich environment. When the LATS was first used to rotate LDEF, materials fell from the surface of many of the trays and a liquid began slowly running from the vicinity of tray C-12. Tray C-12 had been oriented horizontally on the top of LDEF as it sat in the shuttle bay and throughout recovery up until the first rotation in SAEF-2. This liquid was an early indication of atmospheric and/or operationally induced changes to orbitally stable or pseudo-stable materials.

The atomic oxygen degraded materials on the surface of LDEF were a considerable source of particulate contaminants but they were not the only source of particles in SAEF-2 and an additional set of new particles began accumulating on the satellite. Contaminants in SAEF-2 were monitored by automatic particle counters and by fallout and witness plates. Tapelifts were also taken of the surface of LDEF. The trays containing the experiments were removed beginning on February 22 and ending on March 29. A final set of tapelifts were collected from LDEF on April 13 and 14. Boeing was commissioned with the task of extracting contamination information from LDEF surfaces to provide the principle investigators of each experiment on LDEF with background information that may affect their analysis. Specifically the Boeing study was to "determine which contaminants were present before the LDEF was flown, which were created during space flight, and which contaminants were acquired by post flight exposures" (MATERIALS SPECIAL INVESTIGATION GROUP HANDBOOK). Our approach was to consider LDEF as a large contamination experiment. This paper is a preliminary presentation of the data collected over the first year since recovery.

When LDEF was considered as a contamination experiment five subexperiments became apparent:

1. LDEF as a particle witness plate for the shuttle bay
2. LDEF as a molecular deposition experiment
3. An experiment to determine the orbital effects on contaminants
4. An experiment to evaluate the accumulation of contaminants in orbit
5. An evaluation of contamination monitoring systems

Each of these experiments has a legacy of data from past missions, from theoretical models, and from basic constraints imposed by physics. The LDEF data is unique in that because of the duration of its stay in orbit second order effects are clearly present that aid in the refinement of models and there is a reduction in the effects of spurious events seen on shorter missions. A summary of the results from each of these experiments is presented below along with a final comment on precautions for principle investigators evaluating parameters that may have been influenced by the presence of contaminants.

LDEF AS A SHUTTLE BAY WITNESS PLATE

The migration of contaminants from the shuttle bay to payloads has been a concern since the beginning of the concept of the shuttle (Ref. 2). The term 'visibly clean' was frightfully unquantitative and anyone familiar with particulate contamination control knew the control of contaminants for such a large and delicate craft was complex in the extreme. A series of sophisticated instruments have been used to try and quantify the amount of particulate matter in the shuttle bay that migrates as a result of launch vibration and other shuttle related events but the results have been circumstantial with respect to the payload and somewhat contradictory (Ref. 3, 4, 5). In the case of LDEF it was the payload itself that was being examined. LDEF provided an excellent opportunity to evaluate the transport of contaminants between the shuttle bay and a payload. As a payload LDEF was exceptional in that it closely paralleled thirty feet of the bay as a large witness plate. There were some problems with this approach in that the preexisting cleanliness level of LDEF had not been ascertained prior to exposure. An additional complication was that the LDEF witness plate consisted of a variety of different surface materials and surface geometries. Each material had a different propensity for retaining contaminants which in some situations was dominated by the specific geometry of the material in terms of how it was attached to LDEF or its orientation. Because of these problems some types of quantitative data would be largely circumstantial. Particle types that were tracers, highly indicative of specific sources, were needed to provide qualitative substantiation and some lower boundary quantification. Because LDEF had been exposed to the shuttle bay on two different occasions a way of differentiating between them was required for a more reliable evaluation of the impact of each exposure. The interaction between particles and surfaces in an orbital environment provided a method for that differentiation in many instances. Below is a summary of what has been accomplished to date.

Pre-Launch Cleanliness of LDEF

The particle cleanliness of LDEF varied significantly from area to area on a tray, from experiment to experiment, and from tray to tray. Cleanliness was not a priority concern for most of the experiments. Visibly Clean Level II (SN-C-0005) was the only requirement and the expense of elaborate precautions could not and would not have been justified by the original mission goals. Many if not most of the experimental trays were handled with bare hands. Fingerprints and handprints were evident widely dispersed over LDEF and inside the trays (Ref. 1, photograph 6 and Ref. 6, photograph 3).

Contaminants, particulate and molecular, from a variety of sources have been identified as being present on LDEF prior to the exposure to the shuttle. The best estimate for the cleanliness of LDEF prior to shuttle exposure is a modified MIL-STD-1246B Level 2000C, or, using a slope of 0.38 rather than the slope of 0.93 used in the military standard, a level 5000 as presented in Reference 6, "Quantification of Contaminants Associated with LDEF".

LDEF Configuration in the Shuttle Bay and Particle Location

LDEF was located between bay 2 and the SYNCOM cradle in the shuttle bay with its exterior surface approximately a foot from the bay liner. Row 12 was in the 'z' normal position facing out of the shuttle and row 6, on the opposite side of LDEF, was immediately above the floor. Row 3 and row 9 were oriented in the 'x' normal position just below the level of the door hinges. The space end of LDEF was directed toward the shuttle cabin. This geometry is important because it is a configuration unique to the shuttle exposure of LDEF (see Figure 2). In orbit a bifold symmetry about the plane through rows 9 and 3 existed. In LATS a rotational environment with alternating rows directed downward in a unit gravity field defined the exposure. Only in the shuttle was row 12 open and facing upward for extended intervals of time. When the shuttle was rotated to a vertical position the space end acted as a collection plate for fallout from the cabin bulkhead. There have not been enough of the specific surfaces of interest studied to adequately document the results of this geometry for particles but it has been very useful in documenting the arrival of a spray of hydrocarbon containing material at the surface of LDEF (Ref. 1). Work by John Scialdone (Ref. 7) provides a model for selecting surfaces of interest related to the launch environment as well as for the evaluation of some of the micro-environmental effects seen on some trays and reported in Reference 8, "Silver/Teflon Blanket: LDEF Tray C-08".

Tracer Particles and Their Time of Arrival

The best tracer particles for the shuttle bay are the glass fibers used as part of the bay liner and those from the shuttle tiles (Ref. 9, photographs 7 and 8). These are characteristic of the shuttle bay environment and though reported by NASA investigators to be a minor part of the total contaminant burden in the shuttle bay,their durability in orbit makes these fibers an excellent tracer for the bay contributed contaminants. These particles were found widely distributed over the surface of LDEF. The actual number of shuttle glass fiber particles positively identified is less than one hundred but that represents a significant number of the total glass fibers analyzed and is too high a number to suggest that such cross contamination is rare. These small colorless glass fibers could be present at fairly high levels in the shuttle bay and still not be readily visible. The distinguishing characteristics of these fibers are discussed in Reference 9 along with documentation of their post-launch distribution. The shuttle fibers contributed at launch and those that were added during the recovery and transport activities were essentially the same, which complicated the assignment of fibers to those separate events. No attempts have been made at this time to differentiate between them. Many of the fibers deposited originally on the surface of LDEF during launch and present during orbit had moved by the time LDEF was in SAEF-2. Shuttle fibers found on the surface of LDEF in SAEF-2 that were not associated with surface shadows may have been new fibers or relocated older fibers. The relocation of shuttle fibers during recovery operations and their redeposition are documented in Reference 9.

MOLECULAR DEPOSITION EXPERIMENT

Most of the molecular film deposited on the surface of LDEF was the product of LDEF's design and not the result of contaminant residues on its surface at launch. Though before launch LDEF was not particularly clean in the sense of non-volatile residues these residues amounted to less than ten percent of the final film found on LDEF (Ref 1). Over ninety percent of the final film came from materials intentionally used on LDEF, RTV silicone materials and urethane thermal control paints: Z306 black and A276 white. The silicones and the large amount of Z306 paint used on the back side of the trays and on the interior structure of LDEF contributed an estimated two to three kilograms (4 to 6 pounds) of outgassed materials to the environment of LDEF (Ref. 6).

Another major factor in the deposition of these films was the geometry of the vents from the interior of LDEF. The vents consisted primarily of the corners of each tray, the edges of the trays, and the edges of the earth and space end panels. All of these vents tended to direct outgassing molecules at low angles over the surface of LDEF. The end panels and the tray edges consisted of openings between two closely paralleling sheets of metal. The most favored escape path was one that nearly paralleled the surface of LDEF. This trajectory kept the molecules in close proximity to the satellite over a greater pathlength, increasing the molecular density near the surface and the probability for an interaction directing a molecule to the surface of the satellite. Where molecules had condensed on a surface that was then exposed to ultraviolet light the molecule was fixed in place or quickly emitted leaving a stable polymerized solid film behind. During the next cycle (cyclic deposition discussed below) the molecules flowing over this surface would not encounter a high density of molecules escaping this surface and so encounters with other molecules would increase the probability of the molecule being directed toward the surface of LDEF. This effect is not dependent upon the RAM effect but rather on vent streams from adjacent trays creating a higher molecular density very near the surface. Considering the amount of vented material available this could account for the deposits seen on the trailing structural elements of LDEF between the trays (Ref. 1, photograph 9). The corner vents consisted of a complex hollow with condensation surfaces parallel to, and normal to, the surface of the tray. The parallel surfaces faced back into the interior of LDEF but were elevated slightly above the face of the tray. The edges of the neighboring trays and the stanchions and longerons constituted collection surfaces at right angles to the face of the tray. These surfaces of the stanchions and longerons faced out onto the trays and would emit molecules paralleling the face of the trays. The double shadows seen around some particles (Ref. 1, photograph 9) could be explained by emissions from these surfaces, both at right angles to the tray surface and to each other.

The vents in LDEF constituted a relatively small opportunity of escape due to their size and the complexity of the escape path for multiple bounce paths. The vent area of LDEF's surface for a single straight path escape was only about 0.2 percent of the total surface. Multiple bounce trajectories or repeated thermal cycling events of vaporization and condensation blended the interior sources into a reasonably uniform composition of molecular species prior to escape. This is indicated by the characteristic uniformity of the infrared spectra of the films found on widely separated surfaces of LDEF (Ref. 1, figures 1, 2, and 6). Another characteristic of the film from the vents was their layering. As many as 34 discreet layers were found in some of these films (Ref. 1, photograph 7). The layers were from tens of nanometers to micrometers in thickness. The most obvious cycle that would result in this layering is that of the orbit. If the cycle was orbital then the majority of the film would have been deposited very early in the mission with relatively high molecular densities and rapid 'fix' times for the polymerization of the films once exposed to ultraviolet light. The film with the 34 or more layers was collected from a vent of tray C-12. C-12 faced out of the shuttle bay and had the earliest exposure to fixing ultraviolet light prior to release into free orbit. Some of these layers may have been fixed in place before LDEF had left the shuttle bay. If this is true deposits on the vents of rows 1, 2, 10, 11, and 12 should be the most developed. Those on the earth and space end should also have a deposition pattern that corresponds to that orientation rather than an orientation dominated by the ram deposition characteristic of LDEF's free orbit. Such a deposit pattern has not been documented for these trays but the search is continuing. Row 12 does seem to have rather well developed deposits compared to row 6 and the apparent thickness of many of the layers seen in these films does seem to support an early, and therefore, orbital cycle deposition sequence.

There is much evidence supporting an orbital deposition sequence but there is also evidence of much longer deposition intervals. The canisters that did not open until a month after entering orbit exhibited depositions of these films. It is possible that some longer cycle was involved in forming some of these layers. Longer cycles have been documented such as thermal variations and ultraviolet light exposure times for different parts of the satellite. The release of some of the film forming materials may have been markedly non-linear with respect to the heating of some collection surfaces. There is no reason to reject multiple deposition scenarios, all occuring at the same time,though one mechanism may dominate in one area for a given interval of time. The rate at which the Z306 and the silicone materials released their outgassing products is not known. There are a number of combinations of release rates, vapor pressures, chemical affinities or stabilities, and rates of interior venting that would account for the composition of the films over the time required for their deposition but it is possible the final film is simply the most stable of a variety of chemical possibilities. Modeling LDEF as a large diffusion tube would help to establish a scale of time over which the amount of material released from surfaces inside could escape to the outside. This has yet to be done. Another long duration source of molecular material is the decomposition and release of fragments of polymers due to the effects of ultraviolet light. Evidence for the loss of material from polymer surfaces through this mechanism is seen on trailing tray Teflon surfaces (Ref 8., photograph 6) and other polymer surfaces.

There were a variety of smaller sources of molecular material on LDEF that had only local effects. These ranged from the microscopic fragments of skin that affected areas on the order of tens of square micrometers, to large packages such as the fiberoptic bundles on tray C-12 that affected areas on the order of a square meter. Each of these small 'diffusion cells' had specific emission rates and and outgassing species that dominated the cell's local environment for some distance dependent upon other local sources and their relative strength. A cellulose fiber outgassing water vapor seems to have created a local zone of protection around the fiber as seen in Reference 9, figure 2, frame 1. The interaction of these cells of various types may help establish the timing of the deposition sequence on LDEF. Determining the timing is critical to understanding how to minimize the effects of these films on satellites or to preventing their deposition on critical surfaces of future payloads.

Though the original molecular film contaminant layer present on LDEF at launch was minor compared to later depositions there were some areas where this pre-launch contaminant was at high enough levels to be of interest. Those deposits were associated with tray clamps and shims or fasteners. In these areas sufficient material had been concentrated by solvent cleaning or other activities to have an effect above the background levels. These objects acted as simple diffusion tubes releasing materials at a rate determined by the volatility of the material, its location with respect to the point of final release into the outer environment, and the temperature at its location on LDEF. The result was a gradient of functional groups that seems to suggest the variability of vapor pressure, release rates, and interaction with the molecular species venting from the interior of LDEF (Ref. 1, figures 17, 18, and 19). These areas should also be useful in developing a better understanding of the formation mechanics of the LDEF molecular films.

CHANGES IN CONTAMINANTS WITH TIME IN ORBIT

Contaminants are not dormant in orbit. Molecular films are an obvious example but particulate contaminants also change and migrate over surfaces in orbital environments. The effect is to increase the apparent footprint of the particle on the surface. In Reference 9, figure 2 a number of examples are provided and are referenced by frame number below in this paragraph. The fractional obscuration of surfaces by particles or the absorption, emission, or scattering of UV, visible, or infrared wavelengths of light are principal areas of concern regarding particles on surfaces. From the standpoint of imaging optics the footprint of a particle is the area of optical inhomogeneity created by the particle. The shadowing effects of particles tends to increase the size of the particles effect by as much as an order of magnitude (Ref. 9, fig.2, frames 1 and 4). Some of this change is due to molecular contaminants that are generally associated with the interface between the particle and the surface on which it sits. If these materials are volatile condensable materials they may spread from the particle along the surface and become fixed molecular films.

The movement of particles from one area of a satellite's surface to another was documented on the ram facing Teflon covered trays (Ref. 9, fig.2, frames 2 and 5). The documented movement was limited to very short distances, less than 100 micrometers, but longer transport distances may also occur though their documentation would be difficult due to the areas that would have to be searched and the number of measurements that would have to be made.

The darkening of molecular films on surfaces with ultraviolet light exposure is a well known phenomena, but with LDEF, knowledge of the nature of the UV modified film and of its optical properties will improve. These molecular films have been implicated in failures due to thermal effects as well as power loss through decreased efficiency of solar cells.

When LDEF was retrieved there was an inhomogeneous distribution of contaminants. That by itself was not surprizing but it raises the question of preferred sites or 'contamination sinks' where contaminants persist or collect preferentially. Reference 8 provides an example of one such location for particles at the edge of tray C-08. The distribution of molecular films on the surface of LDEF is another example. The nature of the specific contamination sink will vary with the type of contaminant and the collection mechanism. Some are active before launch and some are only active in orbit. The concept of contamination sinks may be useful in satellite design.

ACCUMULATION OF CONTAMINANTS IN ORBIT

As a satellite sweeps through its orbit it accumulates man made space debris by impaction. Rapidly moving meteorites from all directions impact with the satellite adding to the accumulated contaminants. The total mass of these two sources is dwarfed by the amount of contaminants they create as a result of the impact. These impacts often generate thousands of times their mass in the form of new particulate contaminants deposited on local surfaces. In Reference 9, figure 3 an example is given of one impact with a bolt and washer on a tray clamp of tray E-10. Droplets of molten metal from the bolt and from the washer were spread over the surface of the clamp at a distance of nearly a centimeter. Many such examples have been found on LDEF, some involving transport on the order of a number of centimeters. Vapor phases generated by these impacts often condense on the surface locally and may redeposit on the satellite's surface at greater distances as part of the return flux in the ram direction. The types of contaminants generated by these impacts is dependent upon the surface impacted. Examples of Teflon, atomic oxygen eroded paint, stainless steel, and anodized aluminum are provide in Reference 9, figure 3. The fluorine detected on many metal surfaces of LDEF may be from the redeposition of materials, gaseous or particulate, created by impacts with Teflon surfaces.

Polymeric materials are another source of new contaminants in orbit as mentioned earlier. Energetic ultraviolet light degrades the bonds holding polymers together, often creating free radicals that may form other bonds or diffuse as an outgassing product into the volume around the satellite. These new outgassing materials are then free to contribute to the molecular films depositing on the surface. This is another possible mechanism for the release of fluorine into the environment of LDEF coming from Teflon and from fluorine catalyzed 934 resin used in many LDEF samples. This deposition should be most prevalent on the ram surfaces (Ref. 10) but due to the atomic oxygen fluence on the ram surface of LDEF carbon based residues would be destroyed though the presence of fluorine and silicon on these surfaces may in part be due to this source. Depositions in the canisters that were closed after ten months may also contain traces of these materials.

Atomic oxygen erosion of paint surfaces liberates inorganic pigment particles that are then free to migrate. Inorganic ash particles or atomic oxygen weakened surfaces are also sources of particles that can become free of the surface as a result of a nearby impact and migrate. Thermal effects may be sufficient to free some of these particles from the surface. There was a very significant relocation of these particles during recovery which would have destroyed any such evidence following recovery. Photographs taken in orbit may provide some information.

EVALUATION OF CONTAMINATION MONITORING SYSTEMS

The presumption of product cleanliness based on the cleanliness of nearby collection surfaces or witness plates, or based on low levels of half micrometer particles in the air as determined by an automatic airborne particle counter is common in high-tech industries. The product itself is often too fragile, inaccessible, or prone to degradation to sample directly. LDEF provided an opportunity to directly examine a surface whose cleanliness, in terms of new contaminants or cross-contamination, had been monitored by environmental sensors placed in proximity to the satellite. The first set of proximal sensors used to monitor the environment to which LDEF would be exposed were all part of the IOCM experiment. This experiment consisted of an impressive array of substrata for later analysis as well as active TQCMs that measured real time variations in the harmonic oscillation frequency of a quartz collection surface (see Ref. 5). These sensors began monitoring the shuttle bay over forty hours before launch and continued through the removal of LDEF from the bay after recovery. The second battery of proximal sensors consisted of witness plates, automated airborne particle counters, and tapelifts from surfaces near LDEF. Tapelifts from nearby surfaces were first collected from the shuttle bay at Edwards, then at Kennedy after the ferry flight, from the canister before and after LDEF's transport from the OPF to the O&C building, and from the LATS until the removal of the last tray in SAEF-2. All of these results were compared to tapelifts taken directly from the surface of LDEF and to direct analysis of selected LDEF surfaces.

In comparing the IOCM results to the tapelift data from the SYNCOM cradle surfaces as well as the shuttle and LDEF surfaces a few apparent inconsistencies are evident. The first has to do with the cross contamination of payload surfaces in the shuttle bay. The analysis of the IOCM data was interpreted as indicating no cross contamination. Tapelift data from the SYNCOM cradle indicated significant amounts of bay liner fiber and tile fiber. It is possible that this material collected on the surface of the cradle prior to activation of the IOCM but some migration of the particles during launch certainly seems likely. The SYNCOM cradle samples were collected in the canister after removal from the shuttle bay with LDEF. A significant amount of LDEF material was present on these tapelifts indicating high levels of cross contamination during recovery activities (Photograph 1). The QCM data failed to indicate particulate deposition of the magnitude that occured. The witness plates, as part of the IOCM, indicated a post flight surface obscuration of 2.4% which closely matches tapelift evidence. The QCM data collected, as currently interpreted, does not correlate well with other analytical method used to monitor the bay, including other parts of the IOCM monitoring system. The QCM's are providing real time data that is potentially of great value but at this time the QCM data from the STS-32 mission is best described as requiring careful and cautious interpretation that must be supported by evidence collected using other techniques.

At some time during the recovery LDEF was 'sprayed' with fine droplets of an organic containing aqueous material that also contained potassium and sodium chlorides. This material has been found on ram facing trays and shows no signs of atomic oxygen degeneration. Its distribution is from row 3 through row 1 and row 12 through row 7. These are the rows that were exposed above the edge of the bay when the doors of the shuttle bay were open and along the port side. None of the IOCM systems detected this event as far as is known at this time. The source of this material is still unknown (Ref. 1).

During the ferry flight the IOCM QCM's behaved erratically, possibly in response to pressure and temperature differences on the exposed crystal created by turbulent flow. Direct examination of the surface of LDEF and paired tapelifts from the same surface before and after the ferry flight indicate significant migration of particles and air erosion of unstable surfaces such as those weakened by atomic oxygen attack while in orbit (Ref. 9, photograph 15). The IOCM witness plates and other surfaces of the IOCM also indicated a very significant redistribution of particles during different parts of the LDEF recovery operation. Small, half millimeter on a side, squares of aluminum coated Kapton from tray D-09 were found widely distributed on LDEF. The shuttle bay floor was littered with them when the shuttle reached the OPF. They were also found on trays B-04, C-12, all over D-09, and in other areas of the interior structure. Reference 9, photograph 14 shows the back side of one of these squares. The other side is vapor deposited aluminum.

The transport of LDEF from the OPF to its final position in SAEF-2 was monitored by witness plates and by tapelifts. The witness plates used to monitor particle fallout at Kennedy were small, 47 millimeter, membrane filter pads. Part of the data is presented in reference 6, figures 1, 2, and 4. The witness plate technique used seemed to lack sensitivity with values at least an order of magnitude lower than tapelift results even when the tapelift results were based only on counts of LDEF materials. Larger particles tended to be even more significantly underestimated on the witness plates resulting in an inversion of the shape of the distribution curve compared to standard models and to the tapelift curves.

Once in SAEF-2 the environment was monitored by automatic airborne particle counter and witness plates. The results of both are illustrated in Reference 6, figures 4 and 7. The SAEF-2 facility was a large room with two exterior walls. The exterior walls had door and window openings. These walls were as much as thirty feet or more high. The air in the facility was provided through diffusers in the high bay ceiling after being filtered through HEPA filters. The air exchange rate was reportedly better than six room volumes per hour. The return air diffusers were in four columns that stood between the high bay and the main work and storage area. The automatic particle counter was on the wall opposite the work area. LDEF was between the work area and the particle counter. Witness plate samples for the room were located near the edges of the room to be out of the way. Witness plate samples were also placed on the LATS to monitor fallout next to LDEF.

The automatic particle counter in the high bay was mounted about ten feet high on one wall of the room. The particle count in the room at that location exceeded 100,000 particles greater than half a micrometer in scattering diameter only for a short time when a twenty foot high scaffolding was being moved in its vicinity. Generally the particle count was less than 10,000 per cubic foot. That included an interval when wood was being sawed in the clean room and an episode during which hundreds of feet of regular chart paper were fed through a high speed chart recorder. Both events left their evidence on LDEF surfaces but neither affected fallout monitor counts or the automatic airborne particle counter (Photographs 1 and 2).

Tapelifts from surfaces in SAEF-2 were collected only to determine the cleanliness of specific surfaces and the types of particulate contaminants present and not to generate fallout rate data. Most of the surfaces that were tested were cleaned once a day but the tape was a more efficient surface cleaner than the method used to clean the surfaces so there was a consistent elevated background. Quantitative rate data can not validly be derived from these results. Tapelift samples were often collected later in the day as a worst case example of cleanliness. Some of these results are shown in Reference 6, figure 2.

Direct examination of LDEF surfaces indicated a steady accumulation of paper fibers, skin flakes, clothing fiber, flooring particles, sawdust, and other materials generated within SAEF-2. Pollen grains, natural minerals, and insect debriswerealso seen,indicating exterior sources for particulate contaminants. The mechanism for the entry of these exterior contaminants is not clear but there are two good candidates. Mechanical transport with the particles being carried in by the large number of personnel in and out of the facility each day is certainly part of the answer. Another is the penetration of contaminants through leaks in doors or windows of exterior walls as a result of wind conditions. The design of the facility makes the establishment of constant positive pressure impractical and certainly not obtainable under the operating conditions when LDEF was in the facility. The pollen types in the samples collected at various times during LDEF's stay in SAEF-2 changed as different plants came into season. A few of the pollen types are shown in Photographs 3 through 6. SAEF-2 has since been remodeled.

CONDITION OF LDEF AS DELIVERED FOR ANALYSIS

All exterior surfaces of LDEF accumulated some contamination from integration with the shuttle bay until release into orbit. The particulate contaminants included skin cells, clothing fibers, paper fibers, clay paper sizing, glass fibers, natural minerals, wear metals of aluminum and iron alloys, and other materials. These particles are identifiable by the shadow effect they had on the surface of LDEF or by orbital environmentally induced modifications of the particle itself. Some surfaces had relatively few surface particles in orbit. Others were quite contaminated. Particle populations varied by a few orders of magnitude over the surface, sometimes even on the same tray. Once in orbit a molecular film was deposited on nearly all exterior surfaces and any interior surface where light could penetrate. The film consisted of hydrocarbon, carbonyl, amine and amide, and silicone functionalities. This film is inert to most solvents but can be scrubbed off the surface. Flushing with organic solvents will not remove this film.

Impacts with space debris or with micrometeorites created additional particulate contaminants including molten metal droplets. Atomic oxygen degraded carbon based materials and silicones generating inorganic ash or silica. Much of the molecular film deposited on the ram facing trays was converted to a film of silica.

Particles from LDEF surfaces began moving to other LDEF surfaces beginning with the grappling of LDEF by the shuttle, if not before. This cross contamination increased and included the shuttle bay surfaces with the turbulent flow of reentry. The ferry flight again exposed the surface to turbulence induced cross contamination. These particles tended to be aluminum film materials, ash, paint pigment, and glass fibers. Some time after grappling LDEF and placing it in the shuttle bay it was showered with a mist of fine aqueous organic liquid droplets with a high water soluble salt content that hit the surface as a slush. These droplet deposits have been found on rows 3, 2, 1, 12, 11, 9, and 7. They seem to be most common on row 12. Row 10 has not been examined for this material. Examination of row 6 materials for the presence of these droplets has been negative to date.

At Kennedy new skin, fibers, pollens, and natural minerals began accumulating on the surface of the trays. On some surfaces the particle count increased by an order of magnitude over the value from orbit. One structural surface increased by two orders of magnitude from the time it arrived in SAEF-2 until the last tray was removed. References 6, 8, and 9 of this proceeding provide additional information.

CONCLUSION

After presenting these five "experiments" it is evident that LDEF has added a great deal to our understanding of contaminants and spacecraft cleanliness. In a broader sense this paper is about materials and systems. When we design a spacecraft and the processes that will be used to construct and deliver it to its final functional environment we are programing reliability into the product. The greatest value of studying the contaminants on LDEF is in deriving information that may aid in the design of more reliable spacecraft. The conclusions below are listed by category with design considerations in mind.

Molecular Films

1. Nearly a pound of contaminating molecular film was deposited on the surface of LDEF while it was in orbit.

2. Although LDEF carried into orbit a surface molecular contaminant film of about 2.5 milligrams per square foot this contributed significantly less than ten percent of the final film burden.

3. The deposited molecular film covering LDEF was the result of outgassing from the urethane paints and the RTV-silicones used on LDEF. These materials were considered space qualified though no bakeout had been performed.

4. The deposited film was layered indicating a cyclic deposition. The cycle may have been an orbit in which case the majority of the film would have been deposited very early in the mission.

5. Fixation of the condensed molecular film required ultraviolet light exposure and possibly some atomic oxygen exposure.

6. Numerous small outgassing sources were present that created local variation in the deposited film.

7. Some outgassing materials seemed to 'protect' small areas of the surface from deposition of films. Some of these materials typically outgas water or other material that is a non-condensable in orbit.

8. A high percentage of the outgassed materials available for the formation of a film contributed to that film. The design of the vents created a high molecular density at the surface by directing much of the venting material parallel to the surface of the satellite. Thermal divergence, the ram effect, and direct impingement explains most of the deposition given the surface concentration.

9. Thermal cycling of surfaces as a result of their exposure to the sun played a significant role in the development of the fixed films. Surfaces that were exposed to the rising sun had thicker films than surfaces that saw the setting sun for any given location. This is believed to be the result of the condensation/evaporation cycle of the molecular film precursor materials prior to fixing by ultraviolet light. The surface that is exposed to the rising sun is always cooler than an adjoining, thermally coupled, surface that is not exposed to the sun until a later time.

10. Organic material associated with potassium and sodium chlorides was deposited as an aerosol over LDEF after it was placed in the shuttle bay for return from orbit.

11. Much of the molecular film deposited on the ram facing tray surfaces was converted to films of oxides of silicon.

Particles

1. The particle cleanliness level for LDEF when it entered orbit was approximately a MIL-STD-1246B Level 2000C.

2. The MIL-STD-1246B particle distribution curve has too steep a slope, 0.93, to represent the distributions seen on LDEF and for most associated surfaces sampled. A slope of 0.4 fits much better.

3. Cross contamination during launch and during recovery between surfaces in the shuttle bay is evident.

4. Particles move along the surface under some conditions in an orbital environment. Thermal effects and local impacts with debris or micrometeorites may provide the force to move the particle and ram effects may be responsible for redeposition. All redepositions of trackable particles occurred on the ram facing trays.

5. Micrometeorite and debris impacts create particulate and molecular debris,a fraction of which collects on the surface of the spacecraft.

6. The majority of the particles on the surface of LDEF while it was in orbit were residues from the assembly of the trays and exposures prior to launch, not transfer from the shuttle bay.

7. The obscuration area of a particle may grow in orbit as a result of outgassing or as a result of shadowing effects involving atomic oxygen, ultraviolet light, or deposition of molecular films.

Shuttle Bay/Payload Cross Contamination

1. Particles move from the shuttle bay surfaces to that of the payload and from one part of the payload to other parts of the payload and to the shuttle bay surfaces.

2. The shuttle bay surfaces have significant populations of free tile and bayliner fiber at the conclusion of the mission. Based on the LDEF study detectable populations of these fibers have transferred to payload surfaces prior to release of the payload in orbit.

3. Shuttle dumps may create debris that lands in part on the contents of the shuttle bay.

4. Reentry and the ferry flight exposed LDEF to turbulent air flow resulting in some erosion of atomic oxygen eroded surfaces and a redistribution of particulate contaminants about LDEF and the shuttle bay.

Contaminant Monitoring Systems

1. In general contaminant monitoring systems did not correlate well with the accumulation of contaminants on the surface of LDEF.

2. The IOCM QCM's detected a number of events of interest but the interpretation of the data is still not clear.

3. The IOCM QCM's behaved in an unexpected manner during the STS-32 mission and ferry flight.

4. The IOCM witness plates provided useful data on contaminants as did the entire exterior surface of the unit.

5. Tapelift samples from the same locations following specific activities provided good qualitative data and appears to provide good quantitative data.

6. Airborne particle counts in SAEF-2 didn't correlate well with activities in the clean room or the particle exposure of LDEF as determined by direct examination of the surface or by examination of tapelifts from the surface.

7. Particle witness plate monitors as used at Kennedy didn't correlate any better than the airborne particle counts. This may have been due to the small size of the plates used, about one square inch. The particle size distribution curves generated by counts from these plates showed an inverted shape deficient in large particles.

Effects of Orbital Exposure on Satellite Cleanliness

1. Contaminants are mobile in orbit.

2. Impacts with space debris or micrometeorites generate quantities of both particulate and molecular contaminants, some of which will contaminate the surface of the spacecraft.

3. Atomic oxygen erosion of carbon based or silicone materials may release inorganic debris on the surface of the satellite.

4. Ultraviolet light breaks bonds in carbon based materials resulting in the erosion of surfaces and the release of new molecular species that may redeposit on the satellite.

5. Particles are often associated with outgassing materials which may increase the effective footprint of the particle once in orbit.

6. Specific types of surfaces may act as local contamination sinks.

These conclusions are based on work still in progress. Much more information can and should be gathered to refine and to add to these conclusions. As important as LDEF is it is still only one data point. As with any good experiment it provided many needed answers but it also generated a whole new set of questions that can best be resolved by future flight experiments. Many of these experiments are already well into the design phase and some are currently being fabricated. LDEF's importance can not be over estimated. It will provide the benchmark against which future progress in the knowledge of contaminants, materials, and systems in space will be compared.

REFERENCES

1. Crutcher, E. R. and K. J. Warner: Molecular Films Associated with LDEF. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

2. Leger, L., S. Jacobs, and H. K. F. Ehlers, "Space Shuttle Contamination Overview", JOURNAL OF ENVIRONMENTAL SCIENCES, Vol. 21, Sept/Oct. 1978.

3. Miller, E. R.: STS-2, -3, -4 Induced Environmental Contamination Monitor (IECM). NASA TM-82524, MSFC, Huntsville, Al, February, 1983.

4. Green, B. David, G. Kenneth Yates, Mark Ahmadjian, and Henry Miranda, "The Particulate Environment Around the Shuttle as Determined by the PACS Experiment", OPTICAL SYSTEMS CONTAMINATION: EFFECTS, MEASUREMENT, CONTROL, SPIE Vol. 777, 1987.

5. Maag, Carl R. and W. Kelly Linder: Measured Space Environmental Effects to LDEF During Retrieval. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

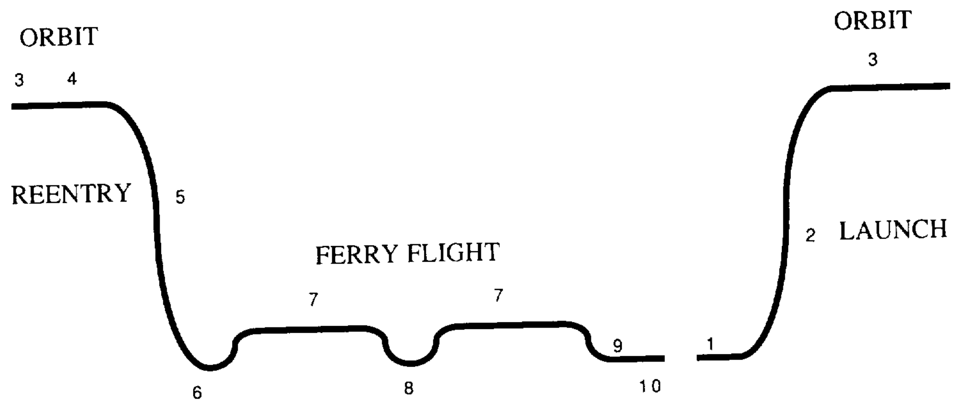
6. Crutcher, E. R., L. S. Nishimura, K. J. Warner, and W. W. Wascher: Quantification of Contaminants Associated with LDEF. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

7. Scialdone, John J., "Particulate Contaminant Relocation During Shuttle Ascent", OPTICAL SYSTEMS CONTAMINATION: EFFECTS, MEASUREMENT, CONTROL, SPIE Vol. 777, 1987.

8. Crutcher, E. R., L. S. Nishimura, K. J. Warner, and W. W. Wascher: Silver/Teflon Blanket: LDEF Tray C-08. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

9. Crutcher, E. R. and W. W. Wascher: Particle Types and Sources Associated with LDEF. First LDEF Post-Retrieval Symposium, NASA CP-3134, 1992.

10. Rantanen, R. O. and T. D. Gordon: Contaminant Buildup on Ram Facing Spacecraft Surfaces. OPTICAL SYSTEMS CONTAMINATION: EFFECTS, MEASUREMENT, CONTROL, SPIE Vol. 777, 1987.



1. Condition of LDEF prior to launch: >MIL STD 1246B level 1000C for many trays.
2. During launch particulate contaminants are redistributed and Shuttle Bay debris is added
3. Contaminants are modified and new contaminants are generated in the orbital environment.
4. Grappling jars particles and films free, some may have relocated of LDEF.
5. During reentry particles and brittle molecular contaminant films relocate.
6. The shuttle is exposed to the Edwards environment, accumulation of natural dusts.
7. High humidity, high gas flow velocities, thermal and pressure stresses occur.
8. HEPA filter fibers appear on tape lifts after exposure to new filters.
9. Ground operations prior to SAEF-2 include many manipulations to LDEF in complex environments.
10. SAEF-2 exposure.

Figure 1. The Contamination Exposure History of LDEF.

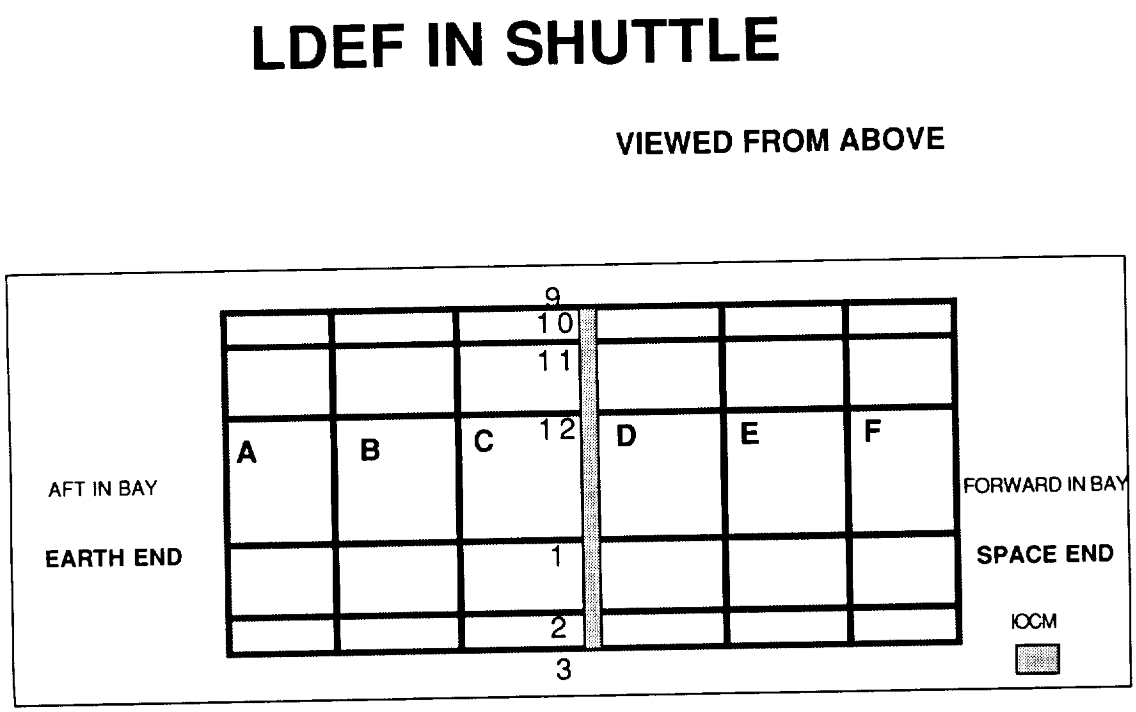


Figure 2. Position of LDEF in the Shuttle Bay.

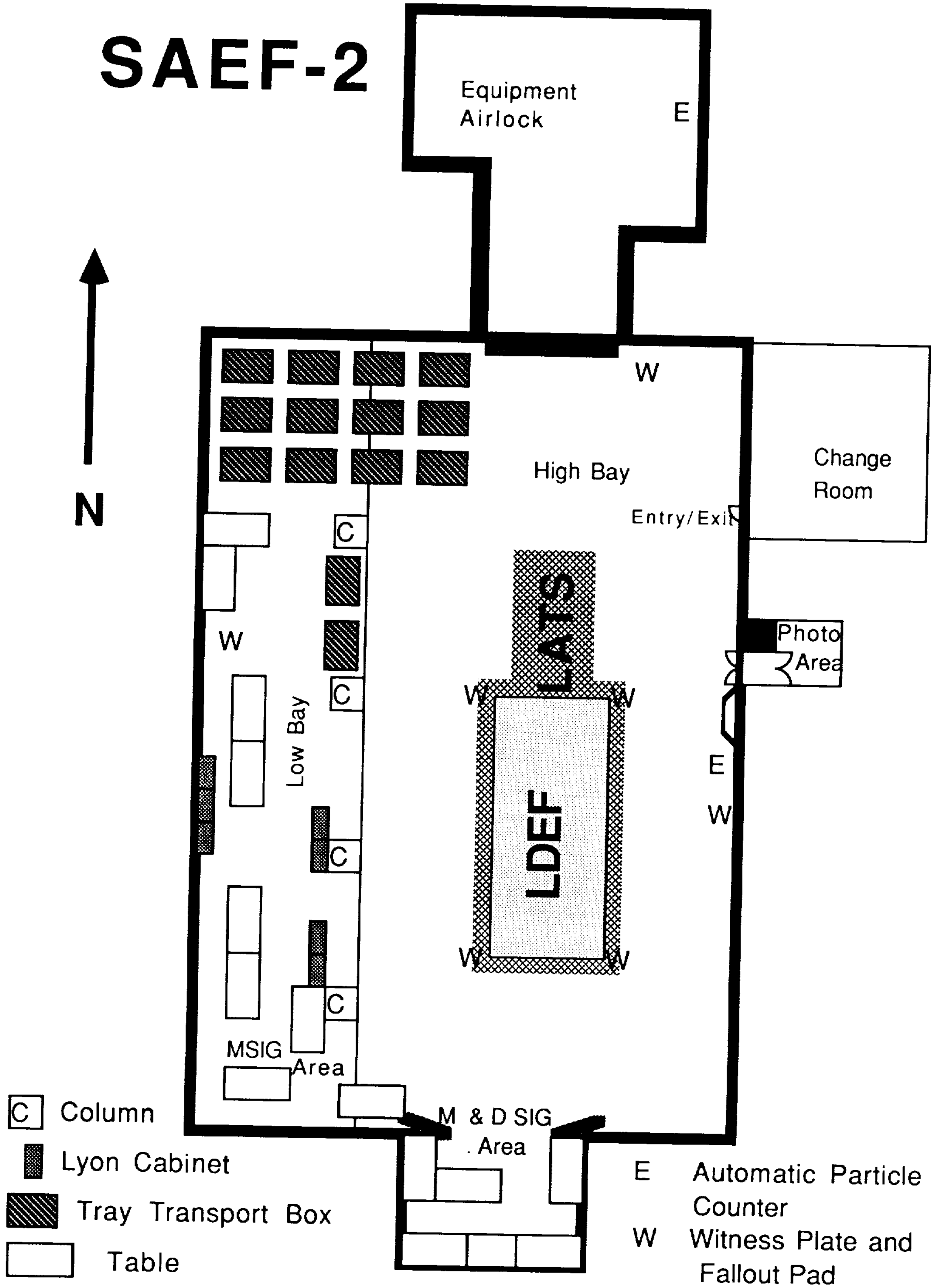
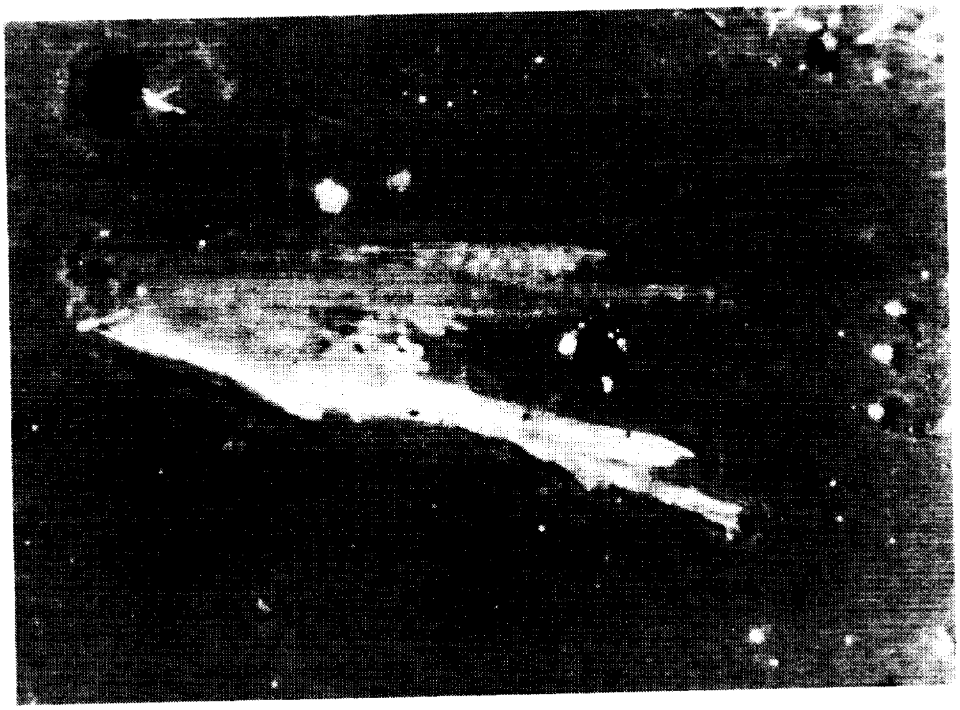
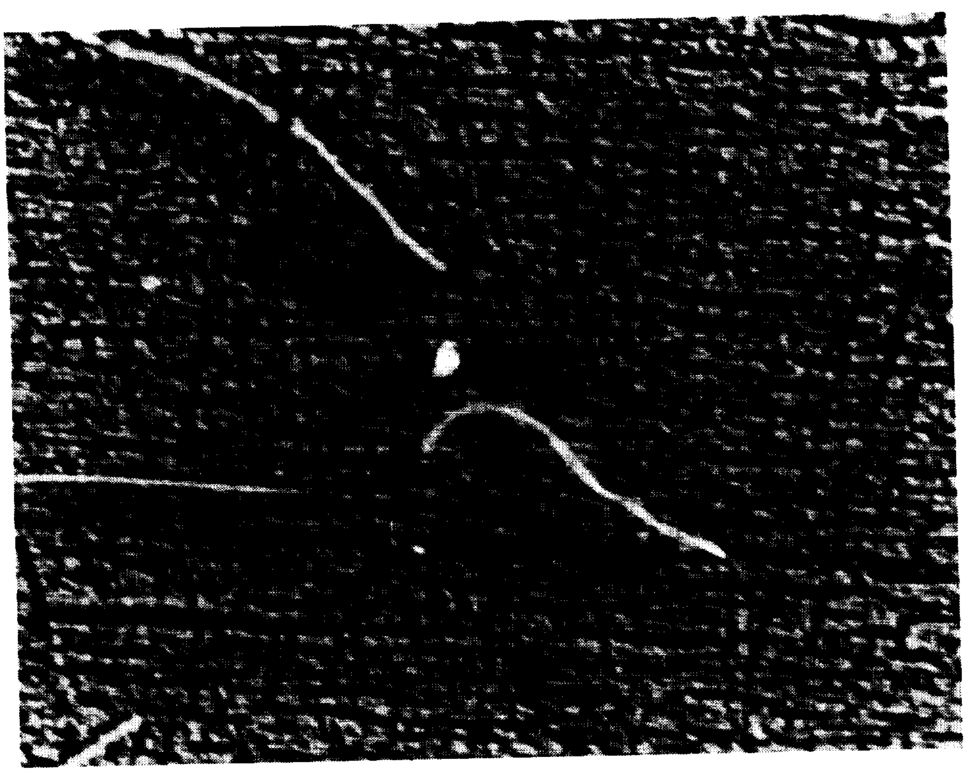


Figure 3. SAEF-2 with LDEF Showing Key Areas.



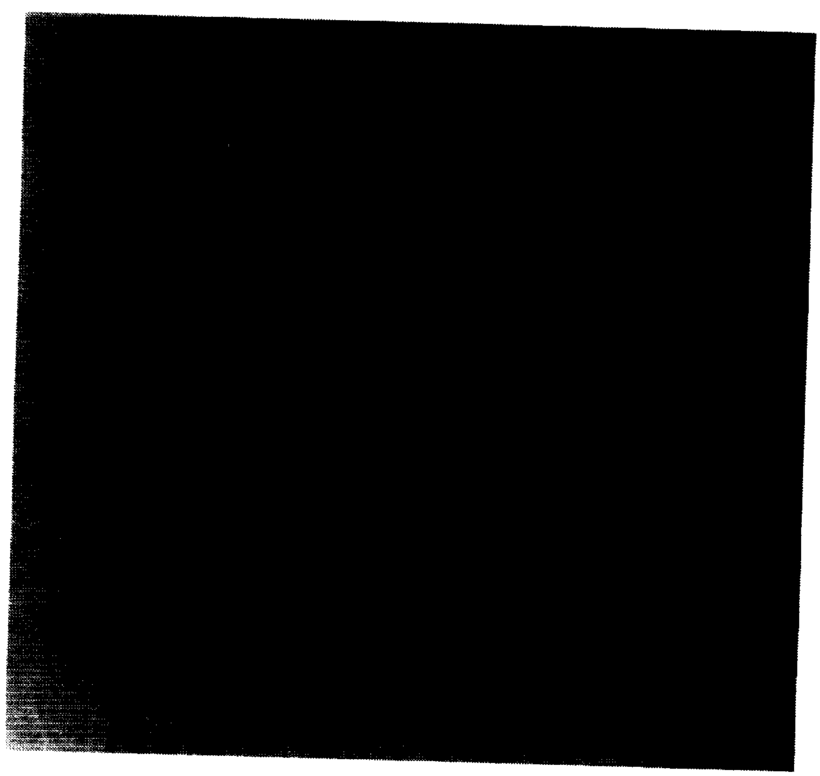
Photograph 1. Sawdust particle from the LDEF longeron surface under the edge of tray D-03. Transmitted illumination of tapelift using slightly off crossed polarized light at a magnification of 100X.



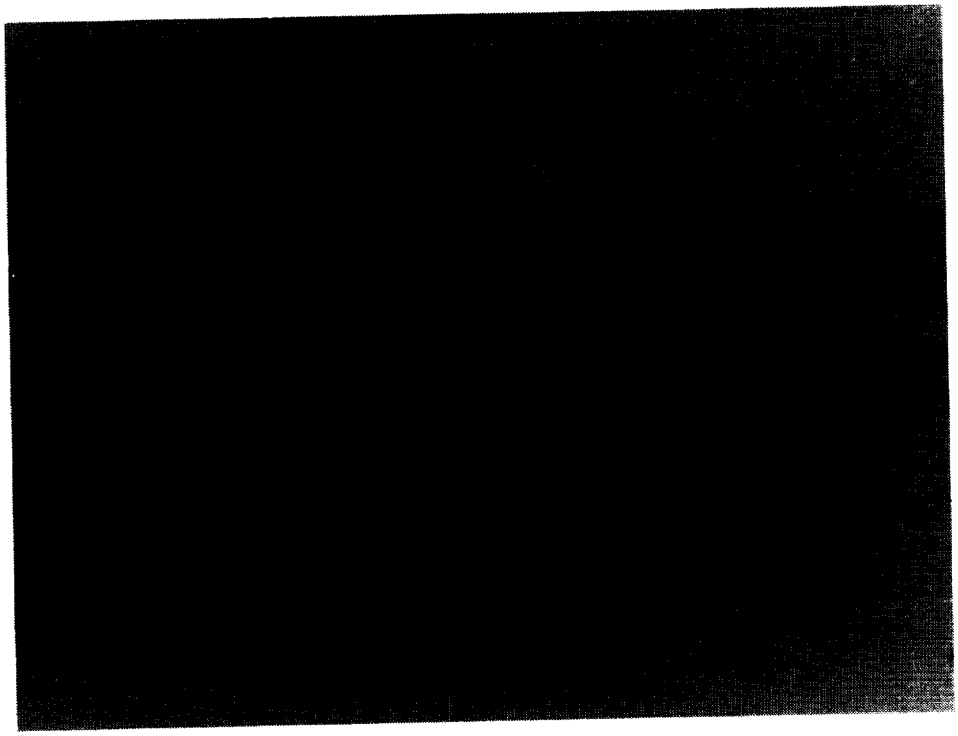
Photograph 2. New and old cellulose fibers of atomic oxygen exposed resin/carbon fiber composit, M0003, tray D-09. Old fiber has been converted to ash. Incident illumination at a magnification of 150X.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

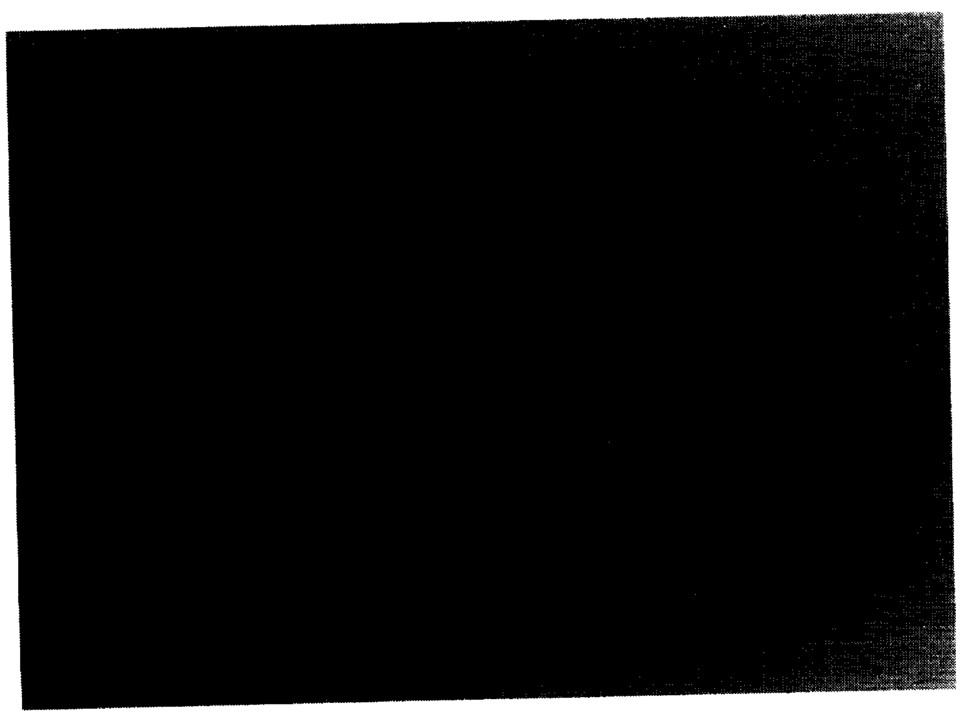
Photograph 3. Pine pollen after brief orbital exposure on shuttle bay surface. Tapelift collected at Edwards. Transmitted light at a magnification of 1,500X.



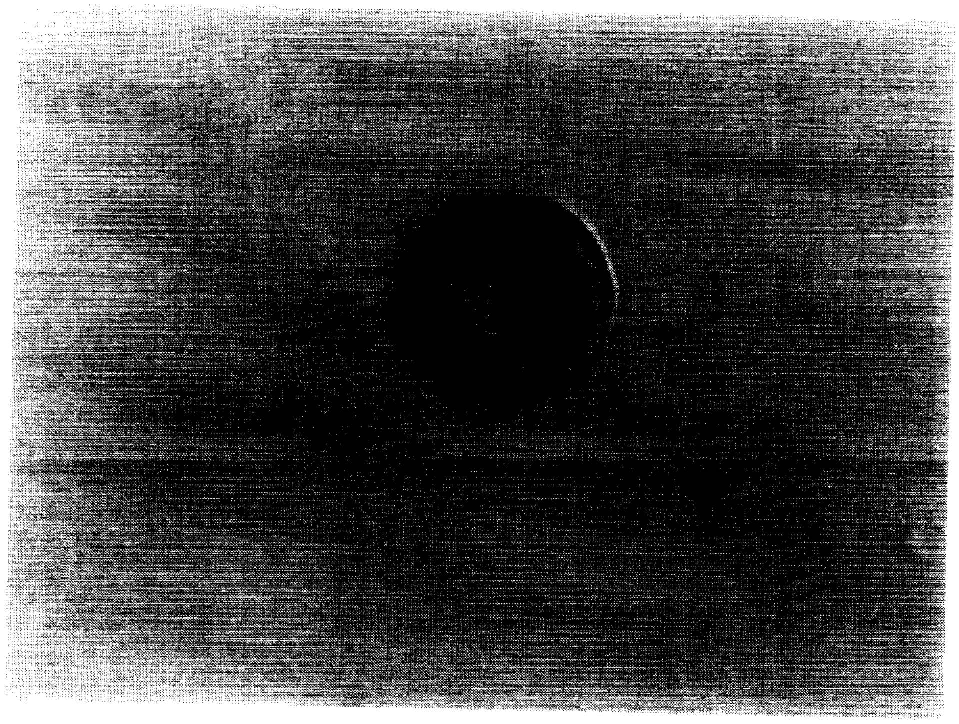
Photograph 4. New pine pollen (yellow) on the surface of tray A-02. Taken in SAEF-2 using Nomarski illumination at a magnification of 320X.



Photograph 5. Willow pollen from the LDEF longeron surface near tray B-09, clamp 6. Tapelift sample collected April 13, 1990. Transmitted illumination at a magnification of 1,100X.



Photograph 6. Pollen from the surface of the LATS under the space end of LDEF. Tapelift sample collected March 16, 1990. Transmitted illumination at a magnification of 1,100X.



Photograph 7. Pollen from the LDEF longeron surface under tray B-08, clamp 4. Tapelift sample collected April 13, 1990. Transmitted illumination at a magnification of 1,100X.