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# EVALUATION OF SEALS, LUBRICANTS, AND ADHESIVES USED ON LDEF

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## SUMMARY

A wide variety of seals, lubricants, and adhesives were used on the Long Duration Exposure Facility (LDEF). This paper discusses the results, to date, of the Systems Special Investigation Group (SIG) and the Materials SIG investigation into the effect of the long term low Earth orbit (LEO) exposure on these materials. Results of this investigation show that if the material was shielded from exposure to LDEF's external environment, the 69 month exposure to LEO had minimal effect on the material. However, if the material was on LDEF's exterior surface, a variety of events occurred ranging from no material change, to changes in mechanical or physical properties, to complete disappearance of the material.

The results presented in this paper are from the following sources: 1) Visual examinations and/or testing of materials performed by various LDEF experimenters, 2) Testing done at Boeing in support of the Materials or Systems SIG investigations, 3) Testing done at Boeing on Boeing hardware flown on LDEF.

## LUBRICANTS AND GREASES

A variety of lubricants and greases were flown on LDEF. With the exception of three lubricant systems flown as specimens in experiment M0003, all lubricants were components of functioning hardware, not the primary item of the experimenter's investigation. Table 1 identifies the lubricants flown on LDEF, where they were located, and a brief summary of their performances. The following paragraphs discuss findings for each of the identified lubricants. The majority of the lubricants were shielded from direct exposure to space and performed their design function as anticipated. However, a $MoS_2$ dry film lubricant exposed to the trailing edge environment completely disappeared.

Cetyl alcohol and a molybdenum disulfide ($MoS_2$) dry film lubricant were used on nut plate assemblies on experiment A0175. Nut plates were coated with either $MoS_2$ or cetyl alcohol. During post-flight disassembly, severe difficulties were encountered with seizure and thread stripping of the nut plates that had been coated with cetyl alcohol. Examples of this are shown in Figure 1. Post-flight inspection of the fasteners installed into nutplates with $MoS_2$ dry film lubricant showed no damage to the threads and nominal removal torques. Fasteners installed into nutplates using only cetyl alcohol sustained substantial damage to the fasteners and nutplates. Post-flight FTIR examination of the nutplates found no remaining traces of cetyl alcohol.

MIL-L-23398 air-cured $MoS_2$ lubricant was used on several components on each of the five NASA provided Environmental Exposure Control Canisters (EECC). The EECC's were located on rows 9 (leading edge), 8, 4, 3 (trailing edge), and 2. The lubricant was applied to the Belleville washers, drive shafts, and linkages (see Figure 2). Portions of the Belleville washers and drive shafts were exposed to the external environment. Visual examination of the EECC located on the trailing edge revealed no evidence of abnormal wear or coating degradation on the surfaces not exposed to UV. Portions of the drive shaft exposed to UV exhibited slight discoloration. Further testing is planned.

VacKote 18.07 and 21207, both made by Ball Aerospace, were used on carousel components of experiment S0069. VacKote 18.07 is a polyimide bonded $MoS_2$ that is sprayed on to the substrate and then cured at elevated temperatures (1 hour at 590F or 50 hours at 300F). This lubricant meets current NASA outgassing requirements. The 21207 is thin pure $MoS_2$ that contains no binder or glue. It is applied by high velocity impingement. Its primary use is in reduction of rolling friction (it possesses poor properties for sliding friction applications). The only post-flight evaluation of either lubricant has been a system functional test of the overall experiment. The system performance was unchanged. To date, no post-flight examination of either lubricant has been performed.

Dow Corning Molykote Z was used on Experiment A0138-10. No results have been reported.

Tungsten disulfide ($WS_2$) dry film lubricant was used as the lubricant on both the rigidize sensing and flight-releasable grapple shafts. This lubricant was used to ensure successful release of the grapple from the RMS during initiation of the active experiments, deployment, and retrieval of LDEF. The grapples performed as designed. The tray containing the grapple used for deployment and retrieval was located 122 degrees to ram and saw an atomic oxygen exposure of 22E+17 atoms/cm$^2$. However, because the shaft extended 3 to 4 inches beyond the LDEF surface, portions of the shaft (and the Teflon tip) were exposed to a much greater fluence. During post-flight analysis at Johnson Space Center, samples of $WS_2$ were removed from both grapple shafts for SEM and EDX analysis. This analysis showed the bulk lubricant to be intact with no discernible difference between the lubricant exposed on the ram surfaces of the shafts and the lubricant exposed on the trailing edges. No surface analysis was performed. To date, the tribological properties of the $WS_2$ have not been determined.

Apiezon H was used as a heat sink grease on experiment A0076, Cascade Variable Conductance Heat Pipe. The grease was not exposed to atomic oxygen or UV. To determine the effect of extended vacuum on the grease, a sample was tested for outgassing in accordance with NASA SP-R-0022A. The LDEF sample had considerably higher total mass loss than the control sample, but the volatile condensible material was similar. It was postulated that this was due to the LDEF sample picking up moisture between satellite retrieval and sample test. Therefore, a series of tests were performed to determine the propensity of Apiezon H to absorb atmospheric moisture. A thin film of the grease was exposed to 100% humidity at room temperature prior to testing. The absorbed moisture caused a total mass loss similar to the difference between the LDEF sample and the control sample. Chemical analysis of the grease indicates that both the grease and the condensible material from the volatility test match those of a control sample. This implies that changes noted in the LDEF material were caused by storage on earth, not by exposure to LEO.

Apiezon L was used on experiment A0180, as a lubricant during fastener installation. To date, it has not been examined.

Apiezon T was used on experiment M0001 as a lubricant for installation of a large O-ring in a flange seal. Examination of the lubricant/O-ring by optical microscopy revealed some slight separation of the oil from the filler. Infrared spectroscopy of the lubricant showed no changes from the control. The O-ring was entirely wetted with the oil and showed no evidence of attack. Post-flight examination of the flange revealed migration of the Apiezon T onto the flange. This migration was not quantified.

Ball Brothers lubricant 44177 was used to lubricate the thrust washer on the five EECC's. A nearby bracket was found to have a diffraction pattern due to the out-gassing of the volatile component of the lubricant as shown in Figure 2. Although the 44177 is still used on previously designed spacecraft, Ball Brothers no longer recommends it for new design.

Castrol Braycote 601 was used to lubricate the four drive shafts which opened and closed the clam shells (canisters) of experiment A0187-1, Chemistry of Micrometeoroids. The drive shafts were located on the exterior surface of tray A3 (trailing edge) but saw minimal direct exposure to UV as the clam shells shielded the drive shafts. Due to the trailing edge location, the 601 saw very minimal atomic oxygen. The lubricant had picked up a black color, as yet not identified, but thought to be some form of contamination. Castrol (manufacturer of Braycote) examined the Braycote 601 with the following results. Infrared and thermogravimetric analysis did not indicate any degradation of the base oil or thickener. Differential infrared analysis of the LDEF Braycote 601 showed it to be virtually identical to new 601. Thermal gravimetric analysis results of the flight sample are very similar to those of a control sample. A slight difference was observed but is likely due to traces of moisture and contamination. No significant change in the temperature at which decomposition begins or in the relative levels of base oil to thickener was observed, indicating that the Braycote was unchanged.

Dow Corning 340 heat sink compound was used on two LDEF experiments, A0133 and M0001. The heat sink compound in both experiments performed as expected, transferring heat from one surface to another. Neither application exposed the Dow Corning 340 to UV or to atomic oxygen. The infrared spectra of a sample of Dow Corning 340 from experiment M0001 were unchanged compared to that of a control sample.

Dow Corning 1102, used on Experiment S1001, Low Temperature Heat Pipe, is an obsolete heat sink compound that was composed of 85% mineral oil, 10% Bentonite, 3% $MoS_2$, and 3 percent acetone. Post-flight visual examination of the material showed no change from the initial condition.

Exxon Andok C was used in Experiment S0069, Thermal Control Surfaces Experiment. No results have been reported.

Mobil Grease 28 was used on the NASA provided magnetic tape modules (MTM). The MTMs contained the cassette tape that recorded on-orbit data. The MTMs were tested and compared to pre-flight measurements. No significant changes were noted. The MTMs were not disassembled so no grease analysis has been performed. No change in the grease was expected as it was in a sealed enclosure backfilled with an inert atmosphere.

Vespel bushings were used in experiments A0147, A0187, and S1002. None of the bushings were exposed to UV or to atomic oxygen. All Vespel bushings performed as expected.

The following three paragraphs describe the results from testing of experiment specimens that were flown as part of a Boeing materials experiment located on the exterior surface of a trailing edge tray (tray D3). These were the only lubricants flown on LDEF that were experiment specimens. All other lubricants were components of a functioning experiment.

DuPont Vespel 21 - Optical and EDX comparison of the flight specimens with control specimens showed no differences. A friction test was performed (in a standard test lab environment) to determine if any changes occurred in lubricity. Four specimens were tested, two flight specimens and two control specimens. The results, shown in Figure 3, verify that the exposure did not degrade the Vespel 21.

Everlube 620 - Post-flight visual inspection of the sample showed that none of the lubricant remained on the test specimen substrates (Figure 4). EDX examination of the surface showed only traces of the $MoS_2$ remaining in the bottom of the machining grooves of the substrate. The binder, a modified phenolic, was apparently decomposed by exposure to UV and then offgassed (evaporated). This led to the $MoS_2$ becoming separated from the stainless steel substrate. This was a failure of the lubricant system, not the lubricant.

Rod end bearings - The bearings were tested at their manufacturer, New Hampshire Ball Bearings, to original specifications. All original test requirements were met including dynamic testing. One of the tests involved removing the PTFE-coated Nomex liner from the bearing body. The force required to remove the liner was similar to virgin bearings. Inspection of the Nomex/PTFE liner showed no degradation. The exterior surfaces of the bearing bodies were cadmium plated in accordance with QQ-P-35, Class 2, Type II. The Type II designation requires that the parts receive a chromate conversion coating after plating. The conversion coating, which was an iridescent yellow brown color, exhibited signs of degradation. Post-flight visual inspection of the bearing bodies showed that the conversion coating had become more transparent. However, this change was not uniform over the exterior surfaces of the three bearing bodies. We speculate that, as has been observed with the aluminum conversion coatings used on LDEF, the hexavalent chromium in the conversion coating has been reduced to trivalent with the associated loss of color. No changes in the cadmium plating were noted.

## SEALS

A variety of seals were used on LDEF, all of them as components of various experiments. These were generally O-rings, although sheet rubber was also used as a seal. In addition, materials that are commonly used for seals were used as cushioning pads. These materials performed as designed, sustaining little or no degradation caused by long term exposure to LEO. The only failure was the ethylene propylene O-rings on Experiment S0069 used to seal the lithium carbon monofluoride (LiCF) batteries. This failure was caused by long term exposure to the LiCF electrolyte (dimethyl sulfite) which caused a compression set to occur in the O-ring. This same phenomenon occurred on ground stored batteries; therefore, this failure is not attributed to space exposure. The performances of these elastomeric materials, listed in Table 2, are discussed in the following paragraphs.

Butyl O-rings were used in face seals on experiment P0004, Seeds in Space Experiment. Because the O-rings were sandwiched between metal surfaces, their exposure was limited to vacuum and thermal cycling. The O-rings were apparently installed without lubricant and sustained some scuff marks and pinching upon installation. Accurate post flight weights of each seed container were taken and compared to preflight values. The results showed no change in weight. This means that the O-rings performed as designed by preventing any desorption of moisture in space (7% of a seed's weight is moisture). There was no evidence of space-induced degradation and the performance of the O-ring seal was as predicted.

The butyl seal used to ensure vacuum inside of the three A0138 canisters underwent post-flight characterization. The seal was bonded to one of the face-plates of the canisters. In the closed position a compression force was exerted on the canister to apply the necessary sealing force between canister halves. When the canisters were in the open position (10 months), the seals were protected from direct exposure to trailing edge environment by an aluminum shield. Tests reveal a slight increase in hardness (4%) but the seals were still in good working order and efficiently adhered to the canisters.

Ethylene propylene (EP) O-rings were used to seal the lithium batteries on experiment S0069, Thermal Control Surfaces Experiment. These seals failed due to excessive compression set of the O-rings. The temperatures seen by the batteries, 13 to $27^{0}$ C, were well within the limits of EP O-ring capabilities. Therefore, failure has been attributed to attack of the O-ring by the battery electrolyte, dimethyl sulfite.

Ethylene propylene diene monomer rubber (EPDM) and acrylonitrile butadiene rubber (NBR) were tested in experiment P0005, Space Aging of Solid Rocket Materials, which was located on the interior of LDEF. As shown in Figure 5, both elastomers exhibited slight changes in strength, modulus and ultimate elongation.

Silicone rubber was used as a cushioning gasket between the sunscreen and the tray in experiment S0050, Investigation of the Effects on Active Optical System Components. Portions of the gasket were exposed through holes in the sunscreen. Since the experiment was on the trailing side of LDEF (row 5), the gasket saw UV, but not atomic oxygen. The exposed areas of the gasket were slightly darkened but did not show any other signs of degradation. The hardness of the gasket was the same in exposed and unexposed areas, and all material was very pliable. Although control specimens were not available, tensile strength and elongation were determined and found to be within the range of other silicone elastomers.

Silicone rubber was also used as a cushioning pad between a metal clamp and some optical fibers in experiment M0004, Space Environment Effects on Fiber Optics Systems. The rubber was mostly shielded, but some edges were exposed to UV and atomic oxygen. The rubber remained pliable and free of cracks. Some darkening of the rubber was observed in the exposed areas.

A large number of Viton O-rings were used on LDEF. Post flight examination showed that the ones examined were in nominal condition. No Viton O-ring seals failed to maintain a seal. None of the Viton O-rings were exposed to UV or to atomic oxygen.

A group of Viton washers was used to pad the quartz crystal oscillators in experiment A0189. The washers were apparently dinked out of sheet stock as a fabric texture was apparent on the flat surfaces. Many of the washers had indentations on one or both of the contacting surface, indicating compression set. No further analysis is planned because the original compression is unknown.

A metal "V" seal was used to seal the pressure valve in the EECC's. The seal was made of Inconel 750 and had a currently unknown finish. It was sealing the stainless steel valve to an aluminum surface. There was no evidence of coldwelding between the valve, the seal, and the mating aluminum surface contacting an aluminum surface.

## ADHESIVES

A variety of adhesives and adhesive-like materials were flown on LDEF. These included epoxies and silicones, conformal coatings and potting compounds, and several tapes and transfer films. Six different adhesive systems were evaluated using lap shear specimens exposed to leading and trailing edge experiments. All other materials were used in assembly of the various experiments flown on LDEF. Typically, these adhesives were shielded from exposure to the external spacecraft environment. The various materials are listed in Tables 3 through 6.

In most experiments, the adhesives were of secondary interest and were only investigated by visual examination and a “Did they fail?” criteria. Because of this role, most adhesive applications had only a few specimens, not enough for statistical data generation. Often, no control samples were kept, and documentation of what was used was occasionally sketchy. With few exceptions, the adhesives performed as expected, that is they held the hardware together. Several experimenters noted that the adhesives had darkened in areas that were exposed to UV. The remainder of this section will document the additional information available on the performance of these materials along with the status of their evaluation.

One of the most obvious adhesive failures on LDEF was on experiment M0003, Space Environment Effects on Spacecraft Materials. In this experiment, four solar cells deposited onto an alumina substrate were bonded to an aluminum mounting plate using an unfilled low viscosity epoxy, Shell Epon 828. On-orbit photographs showed that all four solar cells were no longer bonded to LDEF. No adhesive remained on the cell mounting plates on the leading edge tray but some remained on the mounting plates located on the trailing edge. This indicates that the bond failed at the solar cell interface, and then the adhesive was attacked by atomic oxygen. Epon 828 was used successfully on other experiments so no conclusions have been drawn as to the failure mode. Possibilities include surface contamination prior to bonding, excessive thermal cycling and high loads due to different thermal expansion coefficients between the solar cell substrate and the aluminum mounting plate.

Another adhesive failure occurred on 8 of the 12 polymeric lap shear specimens flown on LDEF's leading and trailing edges. This experiment, M0003-5, included the exposure of 32 - 1"x6" polymeric film strips. The ends of all 32 strips were wrapped around and then bonded to the backside of the mounting plate using a clear RTV silicone (thought to be Dow Corning DC 93-

500). All 64 of these shielded bonds survived the mission intact. 12 of the 32 strips were silverized Teflon foils bonded to aluminized Kapton using the following three different adhesive systems. The adherend for all 12 specimens was the Inconel on the backside of the silverized Teflon and the Kapton.

- RTV 560 plus 12% graphite. RTV 560 is a two part room temperature cure silicone and the graphite is used to increase the electrical conductivity through the bond. Four specimens were located on the leading edge and four specimens were located on the trailing edge. All eight lap shear specimens had become debonded during the mission. Visual examination showed that it was an adhesive failure.
- EC 57C which is a two part conductive epoxy. One specimen was located on the leading edge and one specimen was on the trailing edge. Both bonds were intact.
- Y966, a pressure sensitive acrylic adhesive, was also evaluated. As with the EC 57C, one specimen was located on the leading edge and one specimen was on the trailing edge. Both bonds were intact.

Control specimens exist for all three adhesive systems and the experimenter reports that future plans include testing of both the intact and control specimens.

One other adhesive failed on LDEF. Four out of 40 strain gauges bonded to composite parts on experiment M0003 debonded. The strain gauges, made by Micromeasurements, were bonded to the composites with Micromeasurements MBond 600 and were cured at 200°F. The substrates were graphite-epoxy (1), graphite-polyimide (1), and graphite-polysulfone (2). The strain gauges which were mounted on the shielded side of the specimens saw no atomic oxygen or UV. The specimens saw thermal cycles of -40 to 176°F. The composite substrate had the rough texture of the bleeder cloth used to lay up the specimens. No sanding was done to smooth the surfaces prior to bonding. It is thought that the failures were due to a combination of the thermal cycling and poor surface preparation.

EC 2216 (BMS 5-92) and AF 143 (BMS 5-104), epoxy adhesive lap shear specimens, were flown on the trailing edge. The EC 2216 is a room temperature cure system and the AF 143 is a 350F cure system. Both titanium-composite and composite-composite adherends were evaluated. Composite adherends were T300/934 graphite/epoxy. The lap shear specimens were mounted such that one surface was facing out towards space. Visual examination of the specimens showed the exposed bondline to have become dark brown when compared to the shielded bondline on the backside of the specimens. Five specimens for each of the two epoxy systems were flown (three Ti-composite and two composite-composite specimens for the AF 143 and two Ti-composite and three composite-composite specimens for the EC 2216). The results of post-flight testing are shown in Figure 6. The shear stress values increased 6.8 to 27.8 percent over preflight values. The preflight specimens were tested in 1978. No control specimens exist. The reason for the increase in strength compared to pre-flight values is speculated to be related to continued cure advancement.

A third epoxy system, Hysol EA 9628 250F cure, was also evaluated on LDEF using T300/934 composite lap shear specimens. Three specimens were located on the leading edge and three specimens were on the trailing edge. All six specimens were mounted so one flat surface was facing towards space. The pre-flight measurements were made in 1978 and no control samples exist. The results, shown in the bottom graph of Figure 6, show a decrease in shear strength for all flight specimens when compared to pre-flight measurements and a decrease for the trailing edge specimens (UV only) compared to the leading edge specimens (UV and atomic oxygen). The reason for the difference between leading and trailing edges is unknown as the vast majority of the adhesive is between the mating surfaces and, therefore, shielded from the detrimental effects of the atomic oxygen and UV.

Prior to determination of shear stresses of the above specimens, the epoxy fillets around the edges of the lap shear joints underwent FTIR analysis. This testing was performed to determine if the exposed portion of the adhesive had undergone any physical changes. Comparison of infrared spectra of the shielded Hysol EA 9628 fillets to fillets exposed to UV or UV/atomic oxygen showed the following:

- Absence of the dicyandiamide catalyst from the six shielded fillets that underwent FTIR. Several of the fillets then had their exterior surface scrapped away to exposed new, fresh surfaces. These surfaces then underwent FTIR. Similar results were found with no catalyst identified on these fresh surfaces. The absence of the catalyst is an expected result for thoroughly cured epoxy systems.
- The presence of catalyst on almost all exposed leading and trailing edge fillets. Several of these fillets had their exterior surface scrapped away with the newly exposed surfaces undergoing FTIR. Catalyst was also found to exist in similar quantities. The reason the dicyandiamide catalyst is present on the exposed specimens is most likely due to chemical bonds being broken by the long term exposure to UV. This caused the regeneration or reappearance of the catalyst (or a material with a very similar structure).

Dow Corning 6-1104 silicone adhesive was used to bond velcro to the thermal blankets on the sixteen trays that comprised experiment A0178, A High Resolution Study of Ultra-Heavy Cosmic Ray Nuclei. The bond between the velcro and the blanket performed very well. No degradation of the adhesive was noted.

3M tape 92 ST, a Kapton tape with a silicone adhesive, was flown on experiment A0054, Space Plasma High Voltage Drainage. Peel strength of tape 0.787 inch wide bonded to aluminum was 1.3 pounds on a leading edge tray, 1.2 pounds on a trailing edge tray, and 0.9 pounds for a fresh, unflown tape.

3M tape X-1181, a copper foil tape with a conductive adhesive, was used as grounding straps for the silver/Teflon blankets. The grounding straps were constructed by plying two layers of tape, the adhesives together, with an area of adhesive remaining on each end. A peel test was performed on a sample of the ground strap and compared to a control sample of a freshly constructed strap made from the same roll of tape. All samples had a peel strength of 3.5 to 3.9 pounds per inch. No difference was found between space hardware and ground hardware.

3M tape Y966, an acrylic transfer tape, was used in experiment A0054. The tape was used to bond vapor deposited aluminum (VDA) Kapton film to the aluminum trays. The tape was tested using a 90 degree peel test similar to ASTM D1000 except that tape width was 0.4 inches. Tape from the leading edge tray had a 4.5 pound peel strength while tape from the trailing edge tray had a 3.5 pound peel strength. A ground control specimen made from a different lot of material had a peel strength of 1.4 pounds. The differences may be attributable to tape variations from batch to batch, additional "cure" of the space exposed tape, and experimental variation. Comparison of the failure mode of the tapes from the leading and trailing edge trays showed significant variation. On the trailing edge tray approximately 75 percent of the adhesive stuck to the VDA Kapton while on the leading edge, 85 percent of the adhesive stuck to the aluminum tray and pulled the VDA from the Kapton film.

3M tape Y966 on a silverized FEP film was also used to hold the thermal blankets to the tray frame on experiment M0001. The blankets apparently shrunk in flight causing the blankets to detach from the frame (Figure 7). Portions of the tape were attached to both the blanket and to the frame, having failed across the width of the tape in tension. The film and Y966 remained pliable. Attempts to fail the tape to frame joint in shear were unsuccessful even though a load of roughly 100 pounds was applied to a piece of tape less than a quarter inch wide. The tape was then tested in peel. The Y966 bonded to the aluminum and to the silver on the film well enough to cause delamination of the silver from the film.

3M tape Y8437, a VDA Mylar tape, was used as a coating on the viscous damper shroud, a fiberglass epoxy structure. The tape used on LDEF had a 90 degree peel strength of approximately 4 pounds per inch. After the LDEF tape had been removed, a new piece of the same type of tape (different batch and manufacture time) was applied to the shroud. This tape had a peel strength of only 0.5 pounds per inch. Apparently, the adhesive on the tape sets up with time to give increased adhesion. Space did not appear to have any adverse effect on the tape.

## CONCLUSIONS

A wide variety of lubricants, adhesives, and seals were flown on LDEF. The vast majority of materials flown were not part of the experimenter's initial objectives, but because of LDEF's extended mission, the interest in the performance of these materials was greatly enhanced. Therefore, the Materials and Systems SIG conducted an investigation into the post-flight condition of these materials. This involved documenting what had flown, developing standard test plans for experimenters to use, "inspiring" the experimenters to perform testing on these materials, testing materials at Boeing facilities, and documenting and collating the findings.

One of the two primary conclusions of this investigation was that if the material was shielded from direct or indirect exposure to atomic oxygen and/or UV radiation, the materials returned in nominal condition. The only exception to this was outgassing of the material. While the outgassing proved to have no effect on the material's ability to function as design, in several cases it did contribute to the overall molecular contamination that was throughout LDEF. The other primary conclusion was that if the material is exposed to the exterior spacecraft environment, a thorough knowledge of both the microenvironment that the material will see and how that material will interact with that microenvironment is essential.

| TABLE 1 - LUBRICANTS AND GREASES | | |
|---|---|---|
| MATERIAL - DESCRIPTION | LOCATION | FINDINGS (5/92) |
| Cetyl alcohol | A1 & A7 | Used on nut plates, no traces remain |
| $MoS_2$ | A1 & A7 | Used on nut plates, appears to be nominal |
| $MoS_2$ - Air cured dry film lubricant (MIL-L-23398) | EECCs (shielded and exposed) | No apparent visual change, further testing required |
| $MoS_2$ - chemically deposited | B3 | Degraded |
| Ball Aerospace 21207 - $MoS_2$ | A9 (shielded) | System test results nominal, lubricant not evaluated |
| Ball Aerospace VacKote 18.07 - $MoS_2$ with polyimide binder | A9 (shielded) | System test results nominal, lubricant not evaluated |
| Molykote Z - $MoS_2$ | B3 (shielded) | Not tested |
| $WS_2$ (tungsten disulfide) | Grapples | Bulk properties unchanged, no difference between leading and trailing edge |
| Apiezon H - petroleum based thermal grease | F9 (shielded) | Outgassing tests showed no change |
| Apiezon L - petroleum based lubricant | D12 | Not tested |
| Apiezon T - petroleum based lubricant | H3 & H12 (space end) | Slight separation of oil from filler, some migration |
| Ball Brothers 44177 - Hydrocarbon oil with lead naphthanate and clay thickener | EECCs (shielded) | Not tested, extensive offgassing |
| Castrol Braycote 601 - PTFE filled perfluoronated polyether lubricant | A3 | Extensive testing, to date results show no change |
| Dow Corning 340 - Silicone heat sink compound | Shielded | IR spectra unchanged |
| Dow Corning 1102 - Mineral oil based heat sink compound | Shielded | Appearance unchanged |
| Exxon Andok C - Petroleum grease | Shielded | System test results nominal, lubricant not evaluated |
| Mobil Grease 28 - Silicone grease | MTMs (shielded) | System test results nominal, lubricant not evaluated |
| DuPont Vespel bushings - polyimide | Various | Appearance unchanged |
| DuPont Vespel 21 - Graphite filled polyimide | D3 | Optical, EDX, and friction tests showed no change |
| E/M Lubricants Everlube 620C - $MoS_2$ with modified phenolic binder | D3 | Complete binder failure, only minimal traces remained |
| Rod end bearings with PTFE coated Nomex liner | D3 | Extensive testing showed no changes |

| Table 2 - SEALS | | |
|---|---|---|
| ELASTOMERIC PARTS | EXPERIMENT | COMMENTS |
| Butyl O-ring | P0004 | 1,4 |
| Butyl rubber seal | A0138 | 1,4 |
| EP O-ring | S0069 | 4 |
| EPDM rubber | P0005 | 1,4 |
| NBR rubber | P0005 | 1,4 |
| Neoprene gasket | A0139 | |
| Nitrile O-ring | M0006 | |
| Silicone gasket | S0050 | 1,2,4 |
| Silicone pad | M0004 | 1,2,4 |
| Viton O-ring | A0015, A0134, A0138-2, A0139, A0180, M0001, M0002, P0005, S0010, S0069 | 1,4 |
| Viton washer | A0189 | 1,4 |
| Metal "V" washer | EECC's | 1,4 |

Key to Comments:

1: Performed as expected, 2: Discolored where exposed to UV, 4: Results discussed in this paper

| Table 3 - SILICONE ADHESIVES | | | |
|---|---|---|---|
| VENDOR | PRODUCT | EXPERIMENT | COMMENTS |
| Dennison | Densil Silicone PSA | A0076 | 1 |
| Dow Corning | 6-1104 | A0187, P0005, A0178 | 1,4 |
| | 43-117 | A0171 | 1,3 |
| | 93-500 | A0171<br>S1002<br>M0003-5 | 1,3<br><br>1,4 |
| | RTV 3140 | S1001 | 1 |
| General Electric | RTV 560 + 12% graphite | M0003-5 | 4 |
| | RTV 566 | A0076<br>A0171<br>S0014<br>S1002 | 1<br>1,3<br>1<br> |
| | RTV 567 | A0054 | 1 |
| | RTV 655 | A0171 | 1,3 |
| | SR 585 PSA | A0076 | 1 |

Key to Comments:

1: Performed as expected, 2: Discolored where exposed to UV, 3: Further testing is planned, 4: Results discussed in this paper

| Table 4 - EPOXY ADHESIVES | | | |
|---|---|---|---|
| VENDOR | PRODUCT | EXPERIMENT | COMMENTS |
| Ciba Ceigy | Araldite AV 100/HV 100 | A0056, A0139 | |
| | Araldite AV 138/HV 998 | A0023, A0056, A0138-1, S1002 | |
| | Araldite AV 138/HW 2951 | A0138-1 | |
| | Araldite AW 136/HY 994 | M0002 | |
| | Araldite AW 2101/HW 2951 | A0138-1 | |
| | Araldite MY 750/HY 956 | A0056 | |
| Crest | 3135/7111 | A0180 | 1,2,3 |
| Emerson & Cuming | Eccobond 55 | A0056,A0139 | |
| | | A0147 | 1 |
| | | S1004 | 1,2 |
| | Eccobond 55 + 10% Ecosil | S1002 | |
| | Eccobond 56C | A0076 | 1 |
| | | A0171 | 1,3 |
| | | S0069 | 1 |
| | Eccobond 56C + Ag powder | S1002 | |
| | Eccobond 57C | M0003-5 | 1,4 |
| Epoxy Technology | Epo-Tec 301 | A0147 | 1 |
| | | S0014 | 1 |
| | Epo-Tec 331 | M0004 | 1 |
| Furane | Epi-Bond 104 | S0014 | 1 |
| Hysol | EA 934 | A0180 | 1,2,3 |
| | | M0004 | 1 |
| | | S1001 | 1 |
| | EA 956 | A0054 | 1 |
| | EA 9210/109519 | M0004 | 1 |
| | EA 9628 | M0003-8 | 1,2,4 |
| Micromeasurements | MBond 600 | M0003 | 4 |
| Rome & Haas | K-14 | A0171 | 1,3 |
| | N-580 | A0171 | 1,3 |
| Shell | Epon 828 | A0056 | |
| | | A0180 | 1,2,3 |
| | | P0003 | 1 |
| | | S1001 | 1 |
| | | M0003-8 | 4 |
| 3M | AF-143 | M0003-8 | 1,2,4 |
| | EC 2216 | A0076,A0138-1, A0178 | |
| | | M0003-8 | 1,2,4 |
| | | S1005 | 1 |
| | | Viscous Damper | 1 |
| Varian | Torrseal | M0006 | |

Key to Comments - 1: Performed as expected, 2: Discolored where exposed to UV, 3: Further testing is planned, 4: Results discussed in this paper

| Table 5 - CONFORMAL COATINGS AND POTTING COMPOUNDS | | | |
|---|---|---|---|
| VENDOR | PRODUCT | EXPERIMENT | COMMENTS |
| Conap | CE-1155 | A0201<br>P0005 | 1 |
| Dow Corning | Sylgard 182 | S1001 | 1 |
| | Sylgard 186 | S1001 | 1 |
| Emerson & Cuming | Stycast 1090 | A0056 | |
| | Stycast 2850 | P0003 | 1 |
| | Stycast 3050 | S0069 | 1 |
| General Electric | RTV 411/511 | S0014 | 1 |
| Products Research | PR 1535 | A0038 | |
| | PR 1568 | A0201 | |
| Thiokel | Solithane 112 | A0178 | |
| | Solithane 113 | A0038, A0178, A0187-2, S0001, S1001, S1002 | |
| 3M | Scotchcast 280 | A0139 | |

Key to Comments - 1: Performed as expected,

| Table 6 - TAPES AND OTHER MATERIALS | | | |
|---|---|---|---|
| VENDOR | PRODUCT | EXPERIMENT | COMMENTS |
| Emerson & Cuming | Eccoshield PST-C | M0003 | |
| Loctite | | A0119, A0138-1 | |
| Mystic Tapes | 7355 | M0001<br><br>P0003 | 1<br><br>1 |
| 3M | 5 | A0139 | |
| | 56 | S0069 | 1,4 |
| | 74 | S0069 | 1 |
| | 92 ST | A0054 | 1,4 |
| | 433 | A0076 | 1 |
| | X-1181 | A0178<br>M0001 | 1,4 |
| | Y966 | A0054<br>M0003-5<br>S0069<br>M0001 | 1,4<br>1,4<br>1<br>4 |
| | Y8437 | A0076<br>Viscous Damper | 1<br>1,4 |
| | Polyester Hot Melt Adhesive | A0133 | 1,3 |

Key to Comments:

1: Performed as expected, 3: Further testing planned, 4: Results discussed in this paper

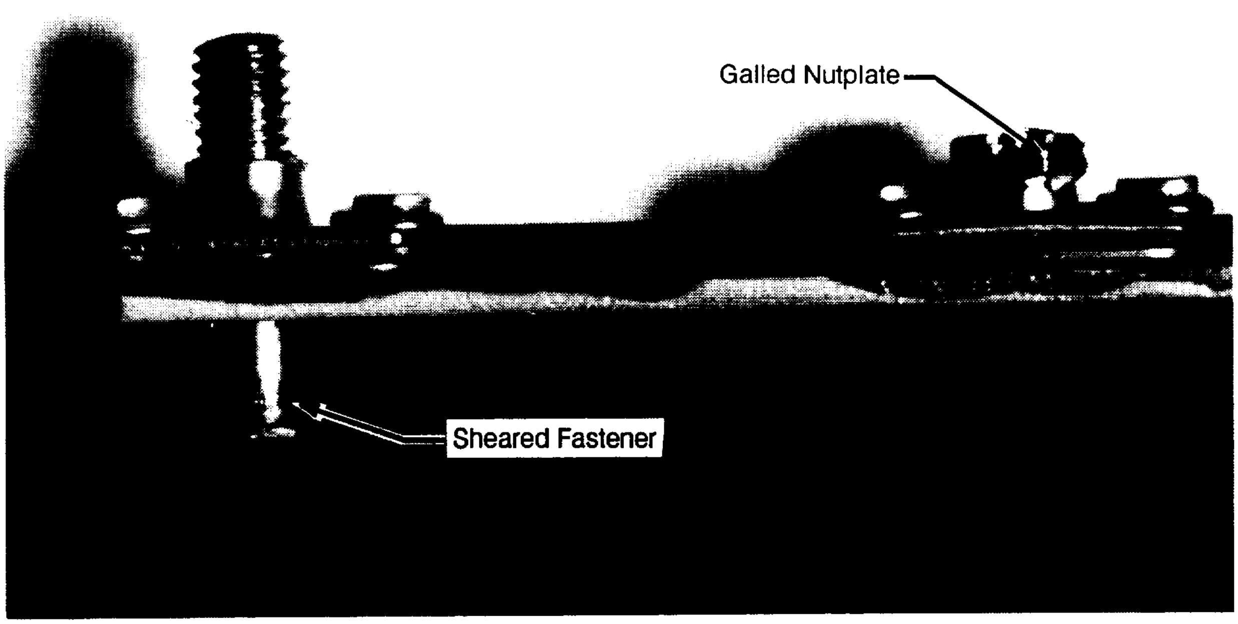



*Figure 1. Sheared Fastener and Galled Nutplate*

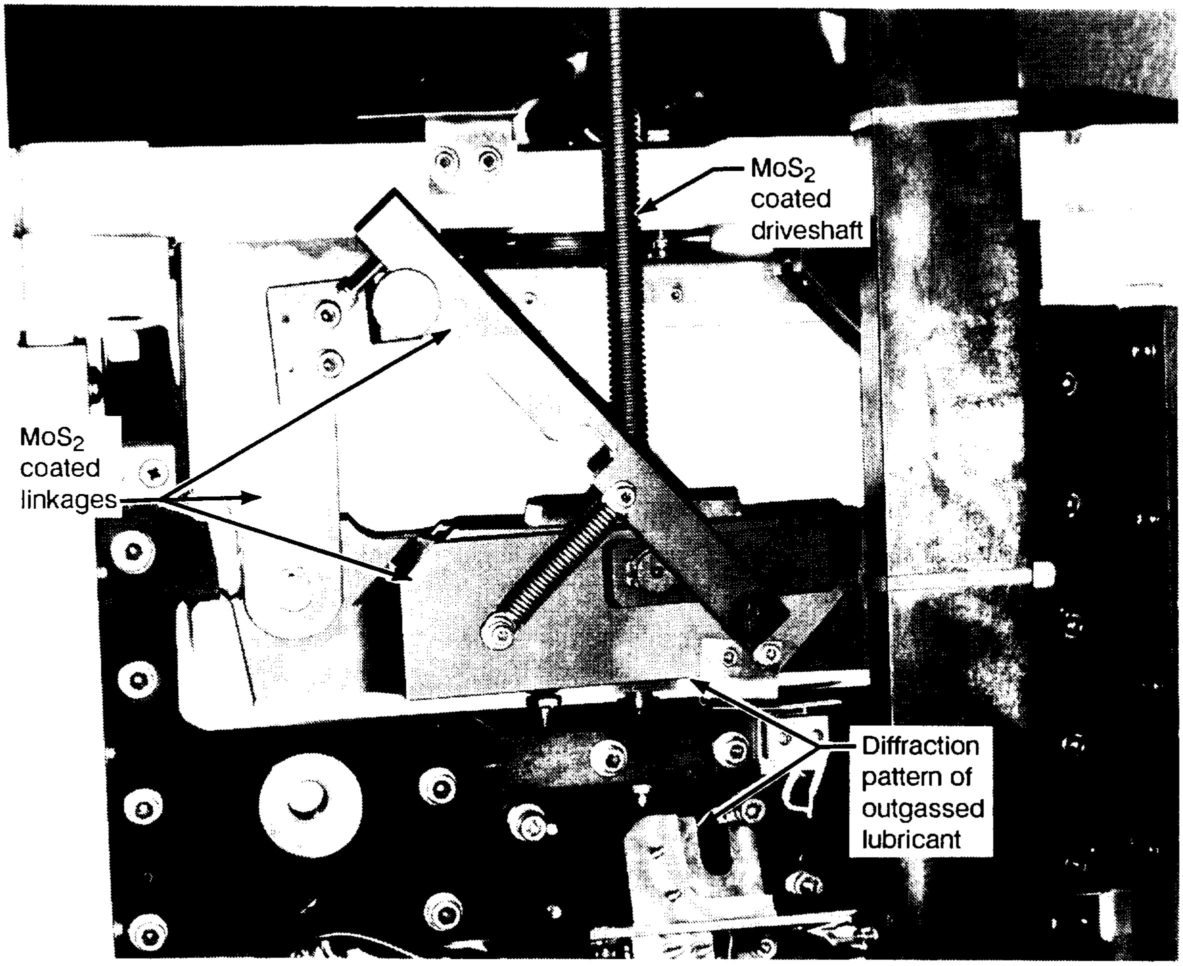



*Figure 2. Lubricant Outgassing Patterns*

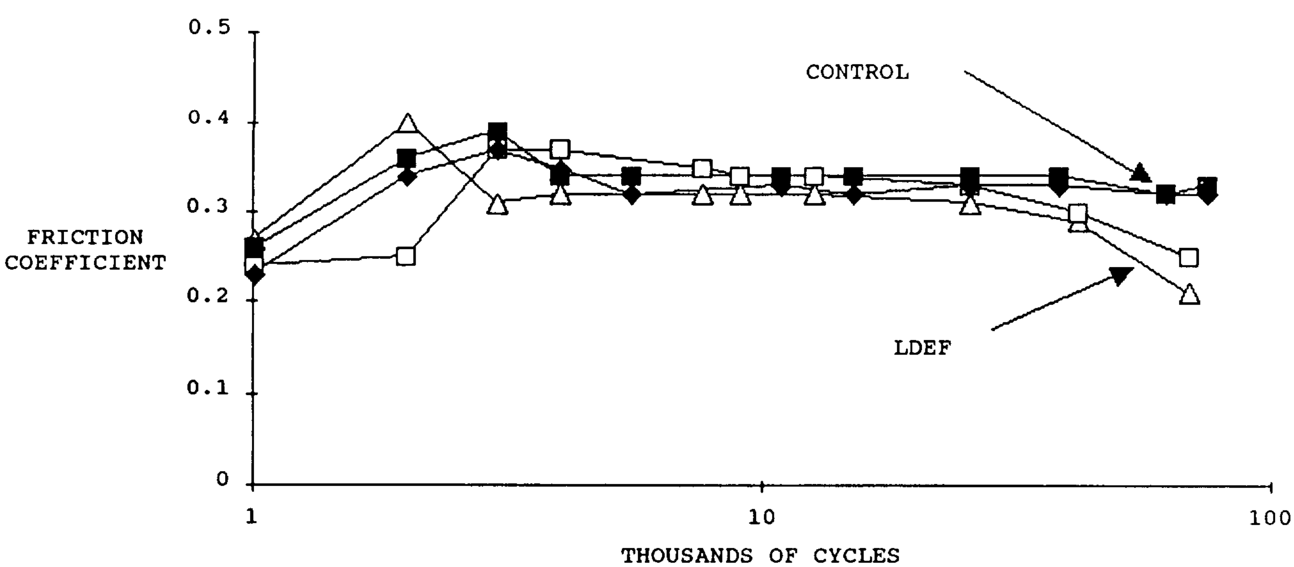
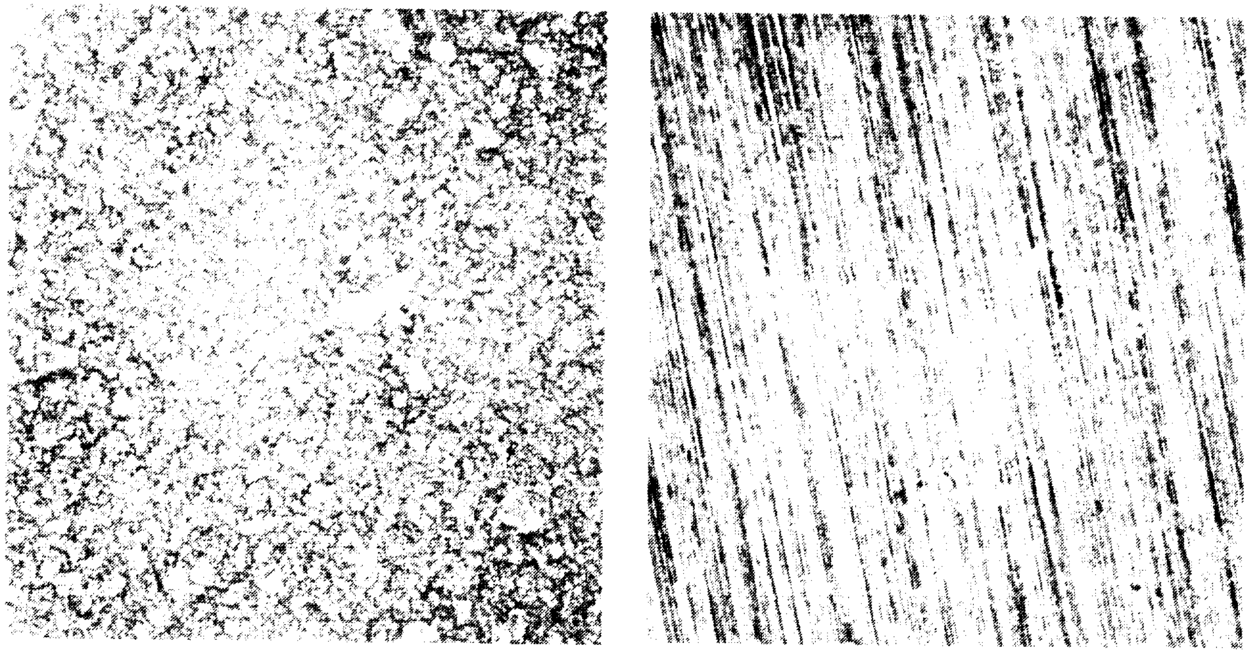



*Figure 3. Friction Coefficient of Vespel 21*



Non-flight Specimen 100X

LDEF Specimen 100X

*Figure 4. Everlube 620C Lubricant*

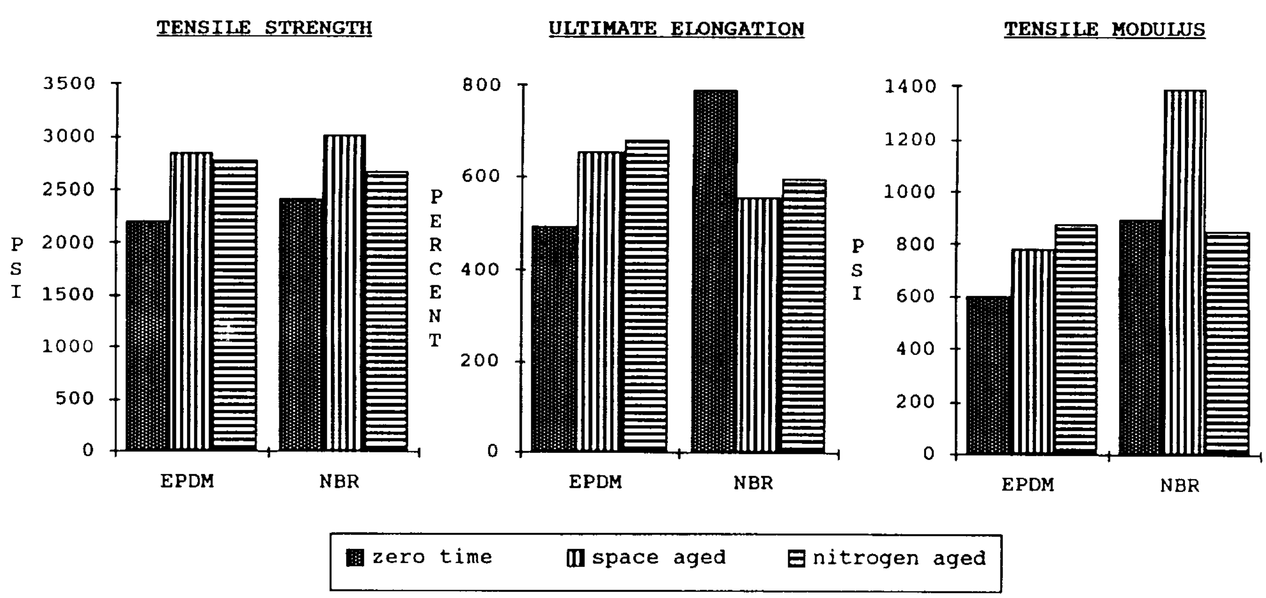
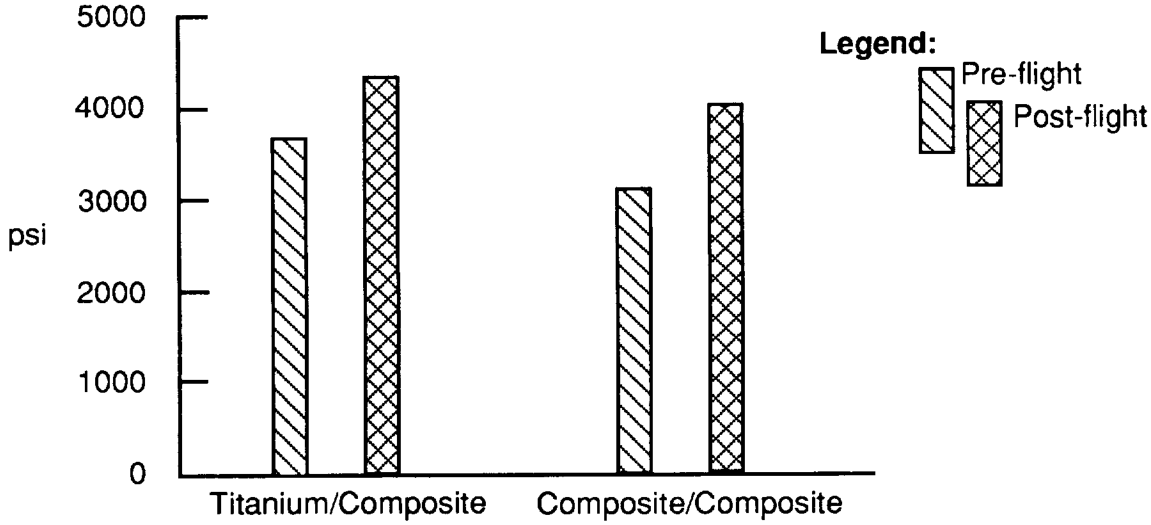
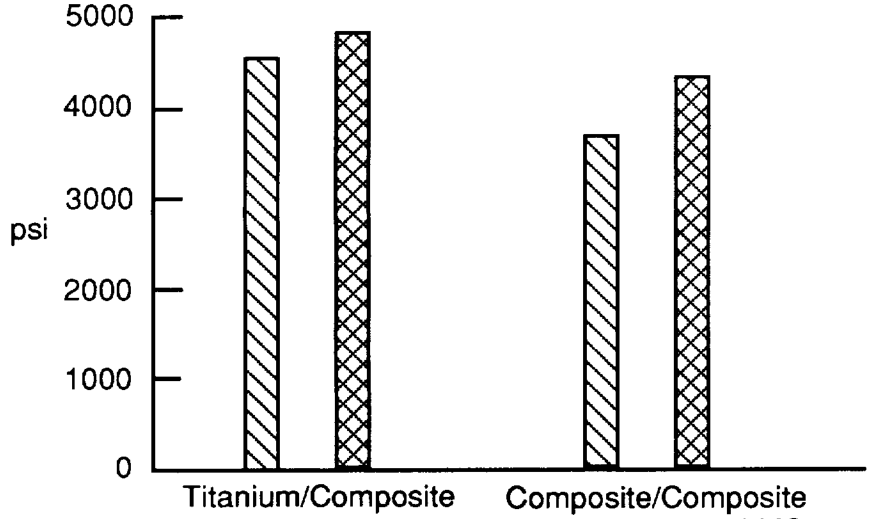


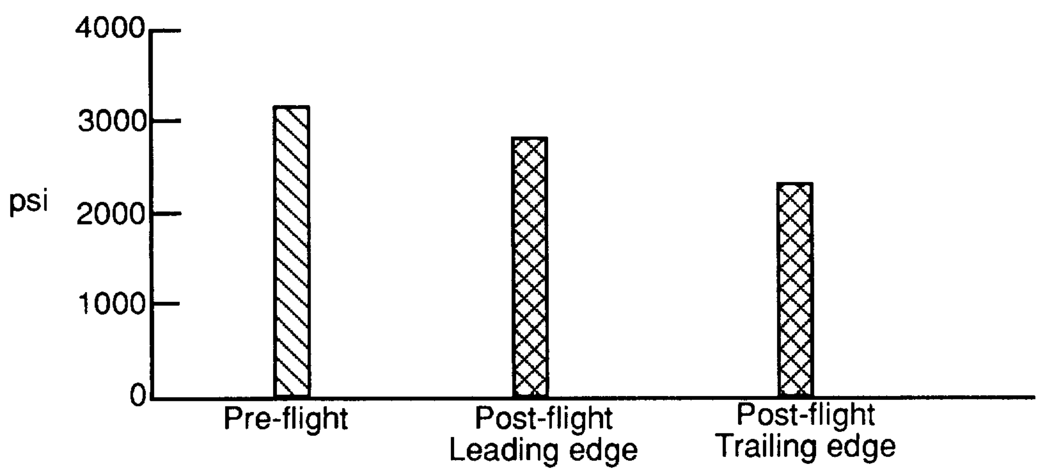

*Figure 5. Mechanical Properties of EPDM and NBR*




- 3M EC 2216 R.T. cure epoxy adhesive (BMS 5-109)
- Trailing edge




- 3M AF 143 350°F cure epoxy film adhesive (BMS 5-104)
- Trailing edge




- T300/934 composite lap shear specimens
- Hysol EA 9628 250°F cure epoxy tape adhesive

*Figure 6. Lap Shear Testing of Epoxy Adhesives Flown on LDEF*

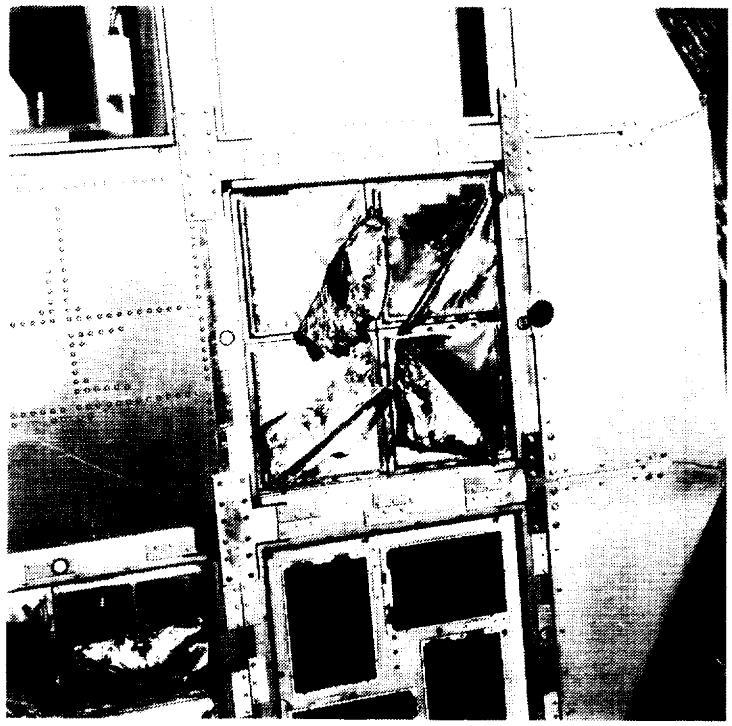


*Figure 7. Loose Silverized Teflon Thermal Blankets*