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Identification and Evaluation of Lubricants, Adhesives, and Seals used on LDEF

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A variety of lubricants, adhesives and seals were flown on LDEF. They were used in the fabrication and assembly of the experiments similar to other spacecraft applications. Typically, these materials were not exposed to U.V. radiation or atomic oxygen, except possibly around the perimeter of the joints.

Most of these materials were of secondary interest and were only investigated by visual examination and a "Did they fail?" criteria. Because of this role, most 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.

LDEF Lubricants

VENDOR	MATERIAL	DESCRIPTION	EXPERIMENT	TRAY
	Cetyl Alcohol		A0175	A1, A7
	MIL-L-23398	Air cured solid film lubricant	EECC'S	
	MoS_2		A0138 A0175	A1 A7
	WS_2		GRAPPLE	C1
Apiezon	H	Petroleum based thermal grease	A0076	F9
Apiezon	L	Petroleum based lubricant	A0180	D12
Apiezon	T	Petroleum based lubricant	M0001	H3, H12
Ball Aerospace Systems Group	VacKote 18.07	MoS_2 with polyimide binder	S0069	A9
Ball Aerospace Systems Group	VacKote 21207	MoS_2	S0069	A9
Ball Brothers	44177	Hydrocarbon oil with lead naphthanate and clay thickener	EECC'S	
Castrol	Braycote 601	PTFE filled perfluoronated polyether lubricant	A0187	A3
Dow Corning	340	Silicone heat sink compound	A0133 M0001	H7 H3, H12
Dow Corning	1102	Mineral oil filled with Bentonite and MoS_2	S1001	F12, H1
Dow Corning	Molykote Z	MoS_2 powder	A0138	

Cetyl alcohol and a molybdenum disulfide (MoS_2) dry film lubricant were used on some of the fasteners on experiment A0175, Evaluation of Long-Duration Exposure to the Natural Space Environment on Graphite-Polyimide and Graphite-Epoxy Mechanical Properties. The dry film lubricant was provided on some of the nutplates and the cetyl alcohol was used to aid in fastener installation. Fasteners installed into nutplates with MoS_2 dry film lubricant showed no thread damage while fasteners installed without the lubricant sustained substantial thread damage. Post-flight FTIR examination of the lubricated treads found no remaining traces of cetyl alcohol.

MIL-L-23398 air cured solid film lubricant was used on several places on the Experimental Environment Control Canisters (EECC). The lubricant was applied to the Belleville washers, drive shafts, and linkages. Examination of the hardware revealed no signs of abnormal wear or coating degradation. Some bare areas where the washers rubbed on each other were apparent on surfaces not exposed to U.V. radiation. Portions of the drive shaft exposed to U.V. radiation were slightly discolored.

Tungsten disulfide (WS_2) dry film lubricant was used as the lubricant on both active and passive grapple shafts to insure successful release of the grapple from the RMS during deployment and retrieval of LDEF. The lubricant on the grapple used for both deployment and retrieval performed as designed. Because the tray was located 22 degrees to the ram, the base of the grapple saw limited atomic oxygen exposure (7.78×10^{21} impacts per square centimeter). However, because the shaft extended three to four inches beyond the LDEF surface, portions of the shaft were exposed to a 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 discernable 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 L was used on experiment A0180, The Effect of Space Environment Exposure on the Properties of Polymer Matrix Composite Materials, as a lubricant during fastener installation. It was not examined after LDEF retrieval.

Apiezon T was used on experiment M0001, Heavy Ions in Space, 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.

VacKote 18.07 and 21207 were used on experiment S0069, Thermal Control Surfaces Experiment. No post-flight examination of the lubricant has been performed.

Castrol Braycote 601 was used to lubricate the four drive shafts which opened and closed the clam shells of experiment A0187-1, Chemistry of Micrometeoroids. Since these drive shafts were exposed to space when the clam shells were in their open position, the Braycote 601 was exposed to some U.V. radiation. However, the experiment was located on the trailing edge of LDEF so the lubricant was not exposed to atomic oxygen. The lubricant had picked up a black color, thought to be contamination. This has not been identified. Castrol examined the Braycote 601 with the following results. Infrared analysis showed no new carbonyl groups, indicating that no oxidation took place. New peaks were found in the 1100 to 1400 range. These might be attributed to C-F bonds indicating some degradation of the PTFE filler but additional investigation is warranted. Some of the LDEF sample was separated into oil and filler by filtration. The viscosity of the base oil was lower than that of a control sample. This would indicate chain sissioning of the polyether and is consistent with exposure to U.V. radiation. Thermal analysis (differential scanning calorimetry and thermal gravimetric analysis) of the extracted oil revealed a new endotherm at approximately 106 C. This may be attributable to moisture effects. The LDEF exposed grease also had an endotherm at 211 C, which was not present in the non-flight sample.

Dow Corning 340 heat sink compound was used on two experiments on LDEF: A0133, Effect of Space Environment on Space Based Radar Phased Array Antenna, and M0001, Heavy Ions in Space. 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 U.V. radiation or to atomic oxygen, but both experiments saw hard vacuum and mild thermal cycling. The infrared spectra of a sample of Dow Corning 340 from experiment M0001 was 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 percent mineral oil, 10 percent Bentonite, 3 percent MoS_2, and 3 percent acetone. Post flight visual examination of the material showed no change from the initial condition.

Dow Corning Molykote Z was used on experiment A0138. No results have been reported.

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 to U.V. radiation. To determine the effect of extended hard 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 percent 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 materials from the volatility test match those of a control sample. This implies that changes noted in the LDEF exposed Apiezon were caused by storage on earth, not by space.

Apiezon H Volatility

TEST SAMPLE	DURATION	TOTAL MASS LOSS	VOLATILE CONDENSIBLE MATERIAL
LDEF	7 DAYS	2.32%	0.66%
LDEF	1 DAY	1.42%	0.44%
CONTROL	7 DAYS	0.97%	0.58%
CONTROL	1 DAY	0.53%	0.18%
CONTROL WITH 2 DAYS HUMIDITY	1 DAY	0.72%	0.21%
CONTROL WITH 1 MONTH HUMIDITY	1 DAY	1.38%	0.25%
MSFC HDBK 527	1 DAY	0.86%	0.16%

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

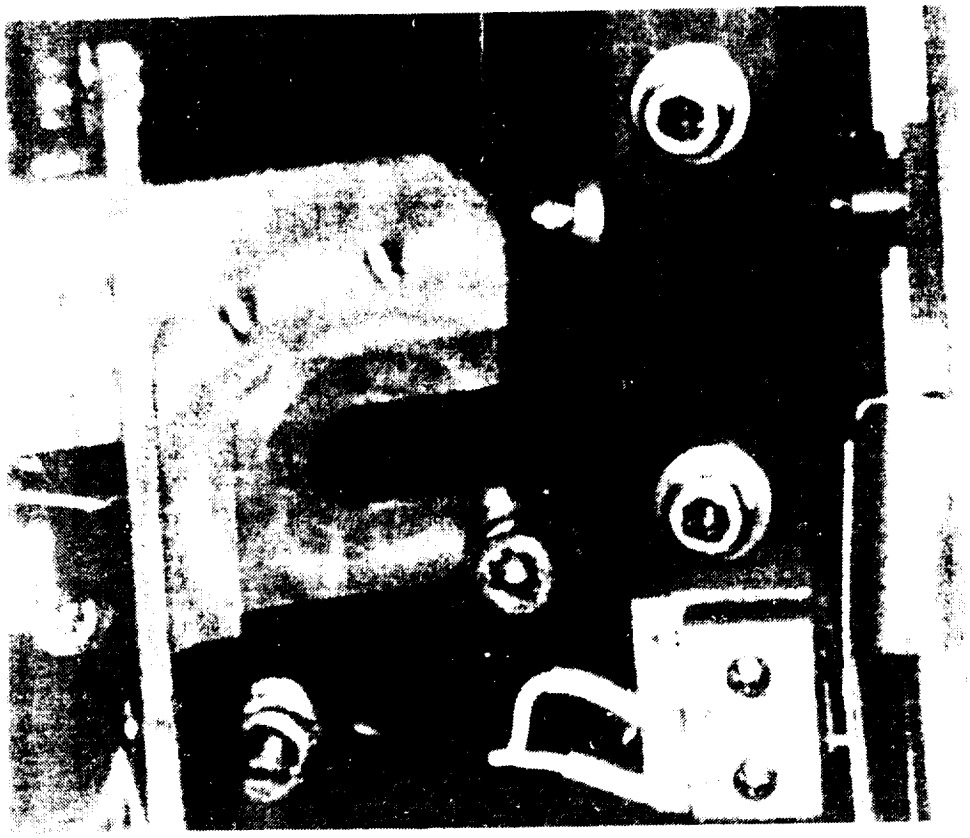


Figure 1. Offgassing Diffraction Pattern of Ball Brothers Lubricant 44177

(Original photograph unavailable)

Vespel bushings were used in experiments A0147, Passive Exposure of Earth Radiation Budget Experiment Components, A0187, and S1002, Investigation of Critical Surface Degradation Effects on Coatings and Solar Cells Developed in Germany. None of the bushings were exposed to U.V. radiation or to atomic oxygen. All Vespel bushings performed as expected.

Everlube 620 was also tested in experiment M0003. Post flight visual inspection of the sample showed that none of the lubricant remained on the test specimens. EDX examination of the surface showed traces of MoS_2 remaining in the bottom of the machining grooves, but not enough material remained to provide lubrication. The binder, a proprietary organic compound, was apparently completely consumed by the environment. Since the experiment was on the trailing edge, the Everlube saw U.V. radiation, but no atomic oxygen. No mechanism for the degradation has been proposed.

Exxon Andok C was used on the carrousel of experiment S0069, Thermal Control Surfaces Experiment and Mobil Grease 28 was used on the magnetic tape memories (MTM's). Both applications were in sealed enclosures backfilled with inert atmospheres. The hardware was tested and compared to pre-flight performances. No changes were expected or found.

Rod end bearings were tested in experiment M0003. The bearings were exposed to U.V. radiation, but not to atomic oxygen. The bearings were tested to the original requirements by the manufacturer, New Hampshire Ball Bearing. All test requirements were met. 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 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 is an iridescent yellow brown color, was mostly removed from parts of the rod end bearings flown on LDEF. Other areas of the bearings that received similar exposure did not exhibit similar chromate coating color loss. No explanation for this phenomena has been proposed.

LDEF Lubricants

VENDOR	MATERIAL	DESCRIPTION	EXPERIMENT	TRAY
DuPont	Vespel 21	Graphite-filled polyimide	M0003	D3
DuPont	Vespel	Polyimide	A0147 A0187-1 S1002	B8, G12 E3
Everlube	620	Heat cured, bonded dry film lubricant	M0003	D3
Exxon	Andok C	Channeling petroleum grease	S0069	A9
Mobil	Grease 28	Nonchanneling silicone grease		mtm
		Rod End Bearings	M0003	D3

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 U.V. radiation.

Epoxy Adhesives

Vendor	Product	Experiment	Comments
Ciba-Geigy	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/HY994	M0002	
	Araldite AW 2101/HW 2951	A0138-1	
	Araldite MY 750/HY 956	A0056	
Crest	3135/7111	A0180	1, 2, 3

Key to comments
1: Performed as expected.
2: Discolored where exposed to U.V.
3: Further testing is planned. Results to be published later.

Epoxy Adhesives (Continued

Vendor	Product	Experiment	Comments
Emerson & Cuming	Eccobond 55	A0056	
		A0139	
		A0147	1
		S0014	1,2
	Eccobond 55 + 10% Ecosil	S1002	
	Eccobond 56C	A0076	1
		A0171	1, 3
		S0069	1
	Eccobond 56C + Silver Powder	S1002	
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	1, 3

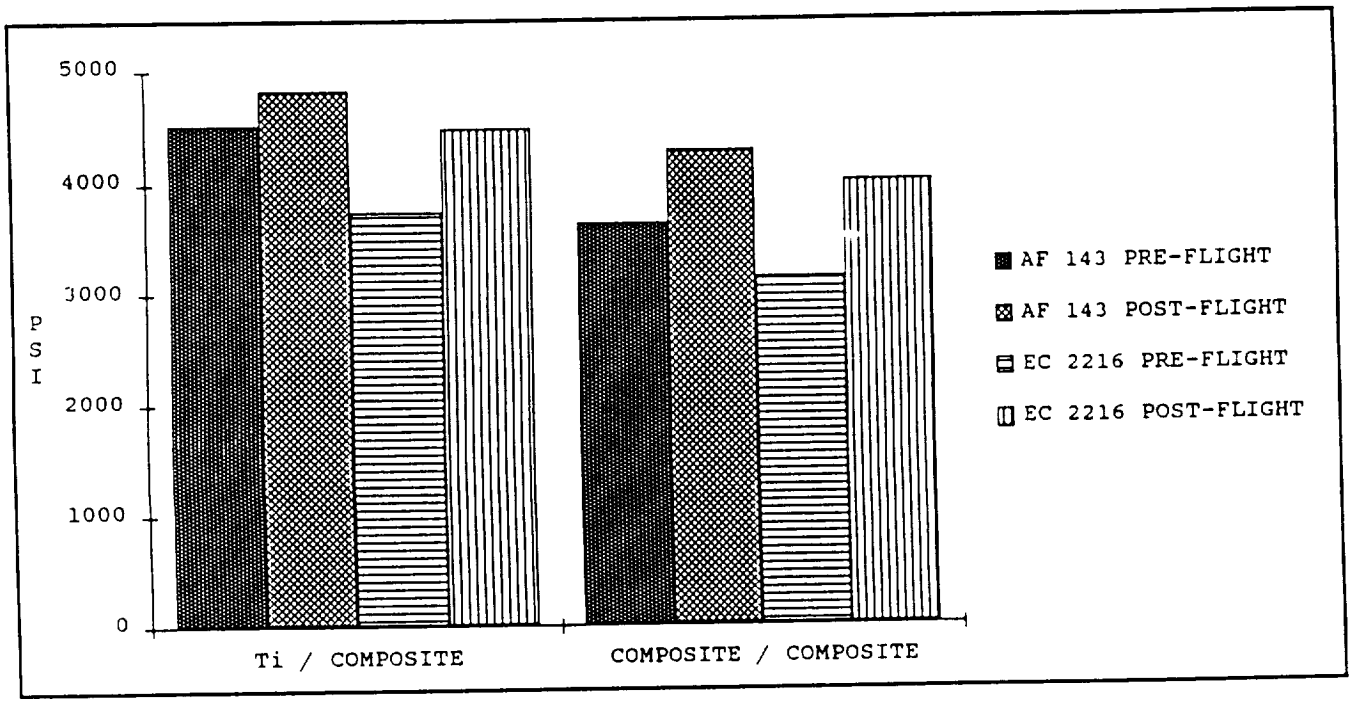
Key to comments
1: Performed as expected.
2: Discolored where exposed to U.V.
3: Further testing is planned. Results to be published later.

Vendor	Product	Experiment	Comments
Rome & Haas	K-14	A0171	1, 3
	N-580	A0171	1, 3
Shell	Epon 828	A0056	
		A0180	1, 2, 3
		P0003	1
		S1001	1
3M	AF-143	M0003	1
	EC 2216	A0076	
		A0138-1	
		A0178	
		M0003	1
		S1005	1
		Viscous Damper	1
Varian	Torrseal	M0006	

The most obvious adhesive failure on LDEF was on experiment M0003, Space Environment Effects on Spacecraft Materials. In this experiment, solar cells were bonded to an aluminum substrate using an unfilled low viscosity epoxy, Shell Epon 828. Photographs taken in space of the LDEF prior to retrieval show that the solar cells were no longer bonded to LDEF. No adhesive remained on the leading edge tray but some remained on the trailing edge tray. 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 loading during takeoff, and excessive thermal cycling and high loads due to different thermal expansion coefficients between the solar cell and the aluminum.

Two 3M adhesives, AF 143 film adhesive and EC 2216 room temperature epoxy, were tested in experiment M0003. Lap shear specimens using graphite epoxy substrates and the test adhesives were exposed on the trailing edge of LDEF. The reason for the slight increase in strength compared to a ground aged sample is not known at this time.

Shear Strength of 3M Adhesives



The only failure of the silicone adhesives was a debond of an FEP film/RTV 560/Kapton film joint. General Electric has postulated that the failure was due to lack of primer rather than to a failure of the adhesive.

Silicone Adhesive

Vendor	Product	Experiment	Comments
Dennison	Densil Silicone PSA	A0076	1
Dow Corning	6-1104	A0178 A0187 P0005	
	43-117	A0171	1, 3
	93-500	A0171 S1002	1, 3
	RTV 3140	S1001	1
General Electric	RTV 560	M0003	
	RTV 566	A0076 A0171 S0014 S1002	1 1, 3 1
	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 U.V.
3: Further testing is planned. Results to be published later.

There were no failures of conformal coatings or potting compounds. All electronic hardware looked very good in post-flight examination.

Conformal Coatings and Potting Compounds

Vendor	Product	Experiment	Comments
Conap	CE-1155	A0201 P0005	
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	
Thiokol	Solithane 112	A0178	
	Solithane 113	A0038 A0178 A0187-2 S0001 S1001 S1002	
3M	Scotchcast 280	A0139	

Key to comments
1: Performed as expected.
2: Discolored where exposed to U.V.
3: Further testing is planned. Results to be published later.

A variety of tapes were flown on LDEF. No adhesive failures of the tapes occurred.

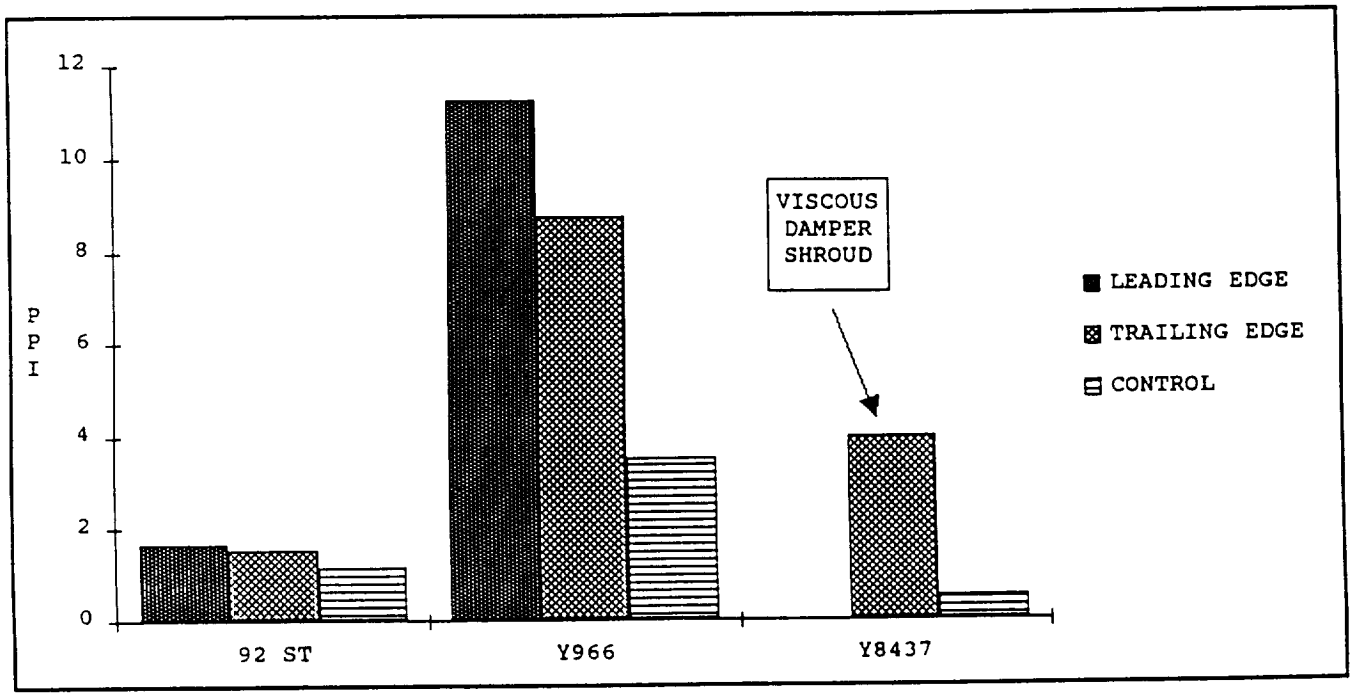
Tapes and Other Materials

Vendor	Product	Experiment	Comments
Emerson & Cuming	Eccoshield PST-C	M0003	
Loctite		A0119 A0138-1	
Mystic Tapes	7355	M0001	1
	7452	P0003	1
3M	5	A0139	
	56	S0069	1
	74	S0069	1
	92 ST	A0054	1
	433	A0076	1
	X-1181	A0178 M0001	1
	Y966	A0054 M0003 S0069	1 1
	Y8437	A0076 VISCOUS DAMPER	1 1
	Polyester Hot Melt Adhesive	A0133	1, 3

Key to comments
1: Performed as expected.
2: Discolored where exposed to U.V.
3: Further testing is planned. Results to be published later.

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 detatch from the frame. Portions of the tape were attached to both the blanket and to the frame, having failed 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.

Peel Strength of 3M Tapes



3M tape 92 ST, a Kapton tape with a silicone adhesive was tested 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 tested 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° 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 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° 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.

A variety of seals were used on LDEF. These were generally o-rings, although sheet rubber was also used for seals. These materials performed as anticipated, sustaining little or no degradation. In addition, materials that are commonly used for seals were used as cushioning pads.

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 only. The o-rings were apparently installed without lubricant and sustained some scuff marks and pinching upon installation. There was no evidence of space induced degradation and the performance of the o-ring seal was as predicted.

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 as shown in Figure 1. The temperatures seen by the batteries, 13 to 27 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.

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, the gasket saw U.V. radiation, but not atomic oxygen. The exposed areas of the gasket were slightly darkened, as shown in Figure 3, 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 U.V. radiation 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 of these found that they were all in pristine condition. No Viton o-rings seals failed to maintain a seal. None of the Viton o-rings were exposed to U.V. radiation or to atomic oxygen.

LDEF Seals

ELASTOMERIC PARTS	EXPERIMENT	TRAY
Butyl o-ring	P0004	F2
Butyl rubber seal	A0138	B3
EP o-ring	S0069	A9
EPDM rubber	P0005	CENTER RING
NBR rubber	P0005	CENTER RING
Neoprene gasket	A0139	G6
Nitrile o-ring	M0006	C2
Nitrile butadiene rubber	P0005	CENTER RING
Silicone gasket	S0050	E5
Silicone pad	M0004	F8
Viton o-ring	A0015 A0134 A0138-2 A0139 A0180 M0001 M0002 P0005 S0010 S0069	G2 B3 G6 D12 H3, H12 LOTS? CENTER RING A9
Viton washer	A0189	D2
Metal "V" seal	EECC'S	

A group of Viton washers was used to pad the quartz crystal oscillators in experiment A0189, Study of the Factors Determining the Radiation Sensitivity of Quartz Crystal Oscillators. 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 surfaces, indicating compression set. A quantitative analysis of this is not meaningful since the original compression is not known.

A metal "V" seal was used to seal the pressure valve in the EECC's. The seal was made of gold plated Inconel 750. It was sealing the stainless steel valve to an aluminum surface. There was no evidence of cold welding between the valve, the seal, and the contacting aluminum surface. No metal transferred between the surfaces.

Ethylene propylene diene monomer rubber, EPDM, and acrylonitrile butadiene rubber, NBR, were tested in experiment P0005, Space Aging of Solid Rocket Materials. The elastomers were not exposed to U.V. radiation or to atomic oxygen, but had extended exposure to hard vacuum. Both elastomers exhibited slight changes in strength, modulus and ultimate elongation.

Properties of EPDM and NBR