NASA Contractor Report 4604

Evaluation of Seals and Lubricants Used on the Long Duration Exposure Facility

H. W. Dursch, B. K. Keough, and H. G. **Pippin**

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June 1994

EVALUATION OF SEALS AND LUBRICANTS USED ON LDEF

FOREWORD

This report describes the results from the testing and analysis of lubricants and seals flown on the Long Duration Exposure Facility (LDEF). Boeing Defense & Space Group's activities were supported by the following NASA Langley Research Center Contracts (LaRC); "LDEF Special Investigation Group Support" contracts NAS 1-18224, Tasks 12 and 15 (October 1989 through January 1991), NAS1-19247 Tasks 1 & 2 (May 1991 through October 1992), and NAS 1-19247 Task 8 (initiated October 1992). Sponsorship for these programs was provided by National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, and The Strategic Defense Initiative Organization, Key Technologies Office, Washington, D.C.

Mr. Lou Teichman, NASA LaRC, was the initial NASA Task Technical Monitor. Following Mr. Teichman's retirement, Ms. Joan Funk, NASA LaRC, became the Task Technical Monitor. The Materials & Processes Technology organization of the Boeing Defense & Space Group performed the five contract tasks with the following Boeing personnel providing critical support throughout the program.

Sylvester Hill	Task Manager
Harry Dursch	Testing and Analysis, Final Report
Bruce Keough	Testing and Analysis, Collation of Results
Dr. Gary Pippin	Data Analysis
Dr. Steve Spear	Data Analysis

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1.0 INTRODUCTION

A wide variety of lubricants and seals were flown on the Long Duration Exposure Facility (LDEF). The vast majority of these materials were not part of the experimenter's initial objectives but because of LDEFs extended mission, these materials became valuable experiments in themselves. Therefore, the Materials Special Investigation Group (SIG) and Systems SIG conducted an investigation into the post-flight condition of these materials. The investigation involved documenting what had flown, "inspiring" the experimenters to perform testing on these materials, testing materials at Boeing Defense & Space Group's facilities, and documenting and collating the findings.

This report discusses the results of the Materials and Systems 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 LDEFs external environment, the 69-month exposure to LEO had, in most cases, minimal effect on the material. However, if the material was on LDEFs exterior surface, a variety of events occurred ranging from no material change, to changes in mechanical or physical properties, to significant erosion of the material.

The results presented in this report were collected 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, and 3) testing done at Boeing on Boeing hardware flown on LDEF.

2.0 LDEF OVERVIEW

LDEF was developed by NASA's Office of Aeronautics and Space Technology and the Langley Research Center to provide a means of exposing a variety of experiments to the LEO environment. LDEF was designed and fabricated at Langley in the late 1970s as a passive satellite which was reusable for planned repeat missions. It was a 14-ft-diameter by 30-ft-long aluminum structure with the cylindrical cross-section of a 12-sided regular polygon. LDEF, weighing 21,400 lbs, was placed in orbit by the Space Shuttle Challenger on April 7, 1984 at a 257-nmi nearly-circular orbit with a 28.4-deg inclination. LDEF was gravity-gradient stabilized and mass loaded so that one end of the LDEF was always pointed at Earth and one side (leading edge, row 9) was always oriented into the orbit path (ram) direction and one side (trailing edge, row 3) was always oriented 180 degrees from ram. Because this orientation remained constant throughout the entire mission, LDEF provided an excellent opportunity to study the effects of the various space environments on materials and systems.

A total of 57 different experiments were flown on LDEF and the experiment objectives ranged from the study of the LEO environment to determining the effect of long-term space exposure on tomato seeds. A schematic diagram of the locations of each experiment on LDEF is shown in figure 2-1. Because of schedule changes and the loss of Space Shuttle Challenger, LDEF was not retrieved until January 12, 1990, after spending 69 months in LEO. Figure 2-2 is an on-orbit photograph of LDEF during retrieval operations. During these 69 months, LDEF completed 32,422 orbits of Earth and traveled almost 750,000,000 nmi. The levels of exposure to atomic oxygen and solar ultraviolet radiation as functions of experiment locations on LDEF are shown in figures 2-3 and 2-4, respectively. Following the Shuttle landing at Edwards Air Force Base and the ferry flight to Kennedy Space Center, the deintegration process began. This process was initiated with the removal of LDEF from the Space Shuttle Columbia on January 27, 1990, and ended 4 months later with the LDEF structure being placed in storage.

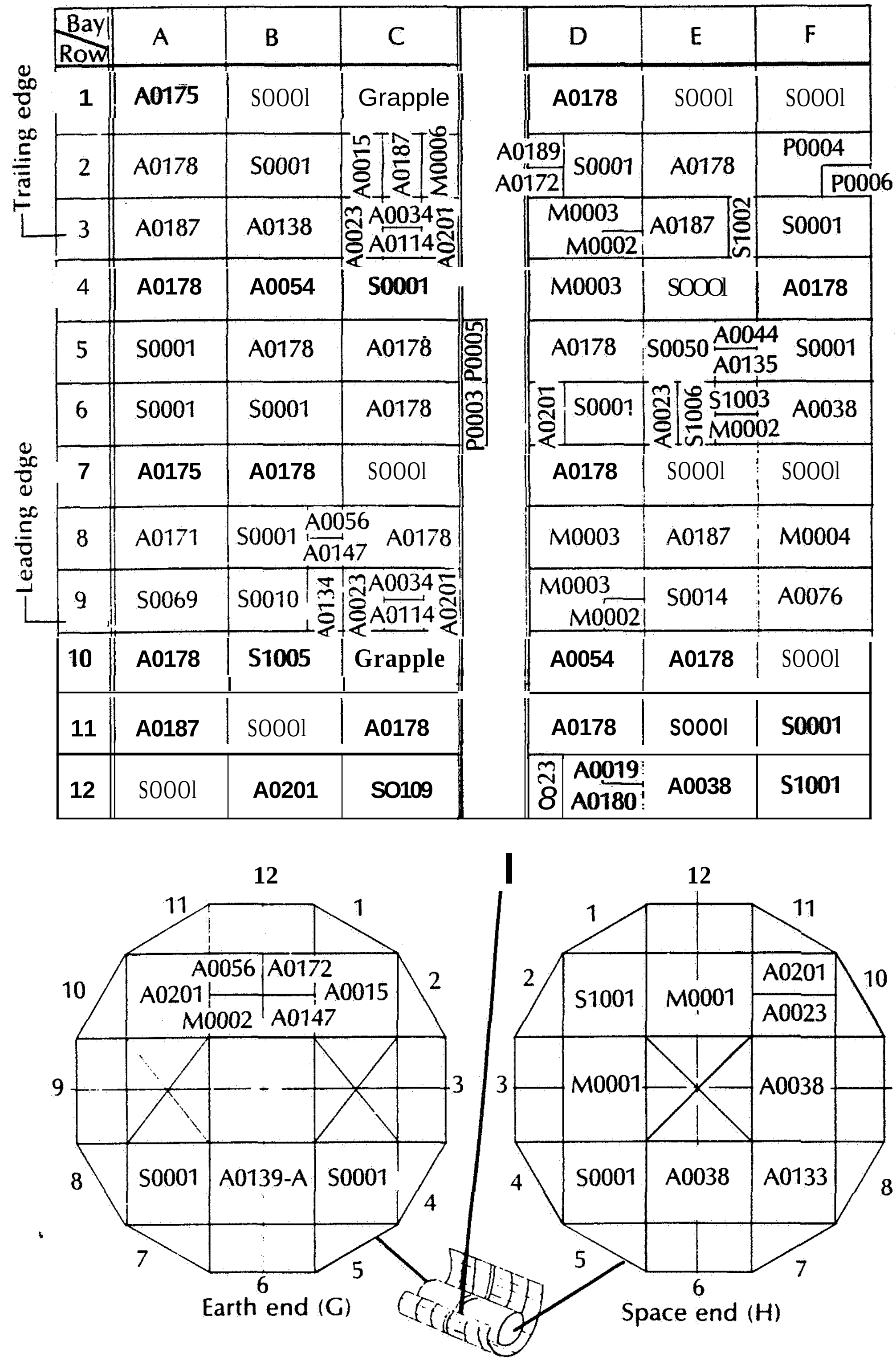


Figure 2-1. Location of experiments on LDEF.

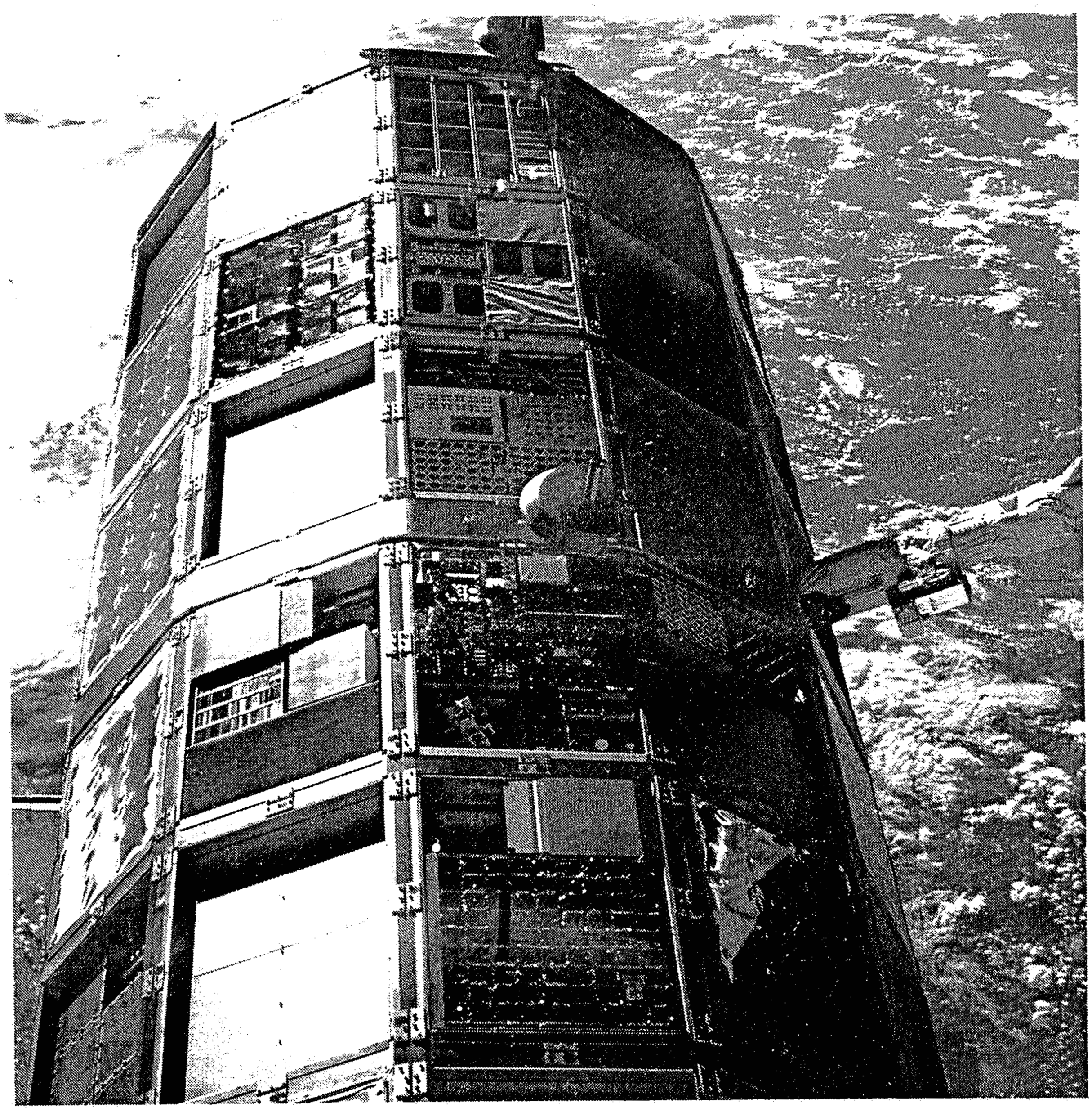


Figure 2-2. On-orbit photograph of LDEF's retrieval showing Row **3** (trailing edge).

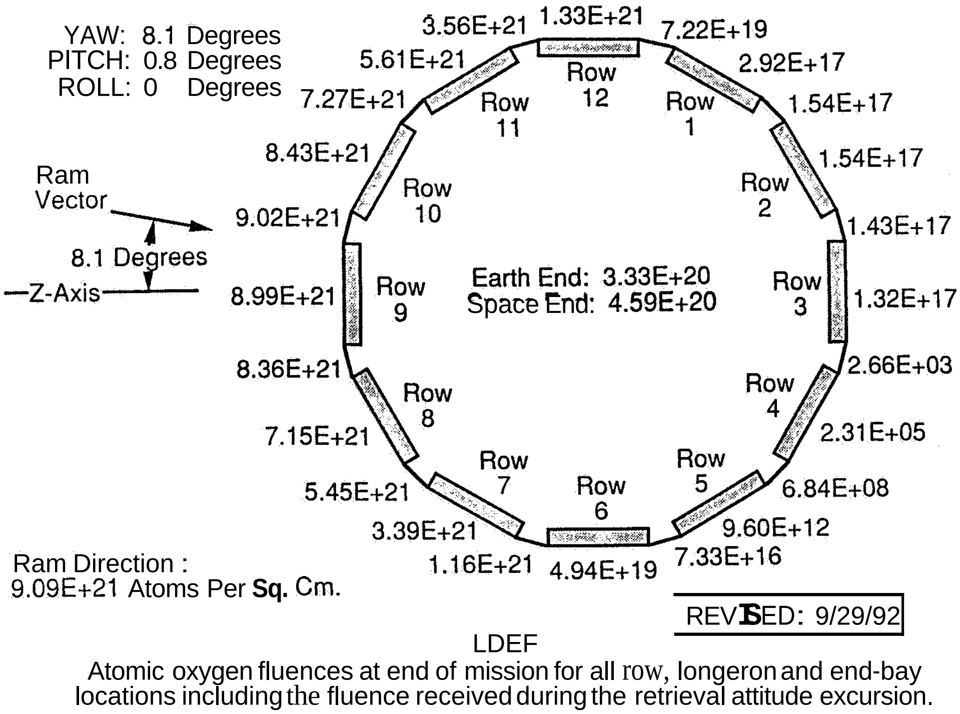


Figure 2-3. Cumulative atomic oxygen fluence for each tray location.

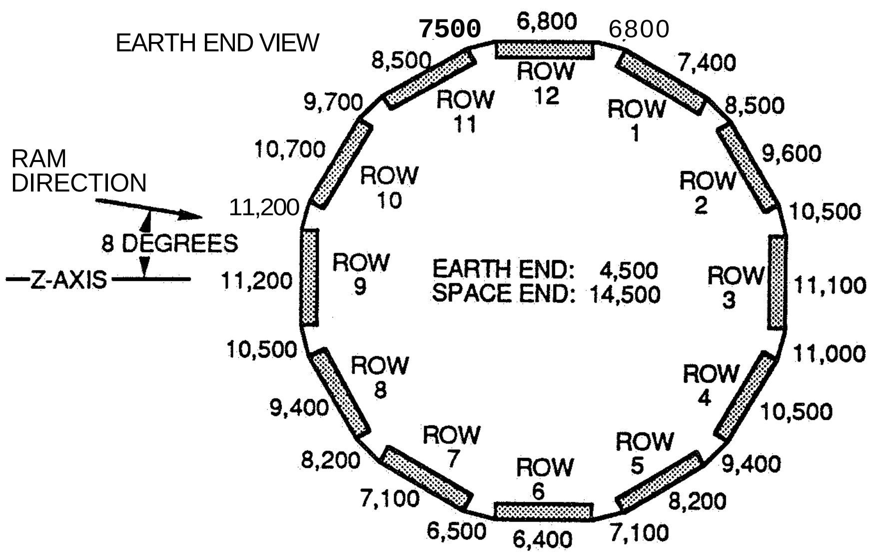


Figure 2-4. Cumulative equivalent sun hours for each tray location.

The extended duration of the LDEF mission, constant orientation to ram, and the successful retrieval presented a unique opportunity to study the long-term effects of space exposure on the more than 10,000 specimens carried on the 57 different experiments. Because of the extended mission length, the science and engineering interest extended beyond the original individual experiment objectives. Four Special Investigation Groups were formed by the LDEF Science Office to assist in the deintegration of LDEF and post-flight analysis of hardware. These four SIGs were the Induced Radiation, Material, Systems, and Meteoroid and Debris SIGs.

3.0 LUBRICANTS

A wide variety of solid (dry) and liquid lubricants were used on LDEF. With the exception of four solid lubricant systems flown as specimens, all lubricants were components of functioning hardware and not the primary item of the experimenter's investigation. Table **3-1** identifies all the known lubricants flown on LDEF, where they were located, and a brief summary of their performances. The following sections discuss findings for each of the identified lubricant materials. Unless described otherwise, all the following materials were shielded from direct exposure to space.

3.1 Solid Lubricants

MoS_2/Cetyl Alcohol

Severe fastener seizure and thread stripping was encountered during hardware removal on LDEF experiment A0175 located on row 1 and row 7. The nut-plates used on this experiment were coated with either molybdenum disulfide (MoS_2) or cetyl alcohol. Unseating and prevailing torques were obtained for the majority of the fasteners by the experimenter. In addition, several fasteners were left undisturbed for additional analysis by the System SIG. Post-flight examination of tray A1 at Boeing determined that all removal difficulties were limited to fastener assemblies that used the cetyl alcohol coated nut-plates. Typical fastener damage is shown in Figure 3.1-1. Post-flight inspection of the fasteners installed into nut-plates coated with MoS_2 showed no damage to the threads and nominal removal torques. The majority of fasteners installed into nut-plates using only cetyl alcohol had excessive removal torques that resulted in substantial damage to the fasteners and nut-plates. Post-flight Fourier transform infrared spectroscopy (FTIR) examination of the nut-plates found no remaining traces of cetyl alcohol. Correlation of removal torque data with the lubrication conditions of the nut-plates showed that while the average unseating torques were approximately the same for both MoS_2 and cetyl alcohol nut-plates at 30 in-lb, the average prevailing torque associated with the MoS_2 nut-plates was 15 in-lb as opposed to 64 in-lb for bare nut-plates. The specification for these type of nut-plates (with MoS_2) requires a prevailing torque range of 2 to 18 in-lb. The excessively high prevailing torques of the bolts using the cetyl alcohol nut-plates is a result of the severe galling from both installation and attempted removal. Therefore, the removal difficulties are directly attributable to the lack of adequate lubrication and galling damage that occurred on original installation and the additional galling on removal. This resulted in seizure, thread stripping, and sheared bolts. *These results show that if the proper lubrication scheme is used, no difficulties will be encountered during on-orbit or postflight removal of fasteners.* The experimenter's eight page post-flight test report detailing the torque measurements and seizing problems is presented in Appendix A.

MIL-L-23398 Air-Cured MoS_2

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 EECCs 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 (figure 3.1-2) of each canister. Portions of the Belleville washers and drive shafts were exposed to the external environment. Visual examination of the trailing edge EECC (tray E3) 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. However, further analysis was not possible because of the difficulty in non-destructively removing the drive shaft from the EECC. Sixteen of the MoS_2 coated Belleville washers were removed from the trailing edge EECC for evaluation. Appendix B is the three-page analytical engineering report. The findings are summarized in the following paragraph.

MATERIAL - DESCRIPTION	LOCATION	FINDINGS
Cetyl alcohol	A1 & A7 - shielded	Failed
MoS_2	A1 & A7 - shielded	Used on nut plates, appears to be nominal
MoS_2 - air cured dry film lubricant (MIL-L-23398)	EECCs -shielded and exposed	Nominal, further testing required
MoS_2	B3 exposed/shielded	Exposed degraded, shielded nominal
WS_2 (tungsten disulfide)	Grapples - shielded and exposed	Bulk properties nominal
Apiezon H - petroleum based thermal grease	F9 - shielded	Chemical analysis and outgassing tests nominal
Apiezon L - petroleum based lubricant	D12 - shielded	Not tested
Apiezon T - petroleum based lubricant	H3 & H12 - shielded	Slight separation of oil from filler, some migration
Ball Aerospace VacKote 18.07 - MoS_2 with polyimide binder	A9 - shielded	Functional test nominal, lubricant not tested
Ball Brothers 44177 - hydrocarbon oil w lead naphthanate & clay thickener	EECCs - shielded	Functional test nominal, lubricant not tested. Extensive outgassing
Castrol Braycote 601 - PTFE filled peffluoronated polyether lubricant	A3 - partially exposed	Extensive testing, results nominal
Dow Corning 340 - silicone heat sink compound	Shielded	IR spectra unchanged
Dow Corning 1102 - mineral oil filled w Bentonite and MoS_2	Shielded	Visual examination nominal
Dow Corning Molykote Z - MoS_2	Shielded	Not tested
DuPont Vespel SP-21; Graphite filled polyimide	D3 - exposed	Optical, EDX and friction tests nominal
DuPont Vespel SP-211; Vespel 21+10% Teflon	D3 - exposed	Optical and EDX tests nominal
DuPont Vespel bushings - polyimide	Various - shielded	Nominal
Exxon Andok C - channeling petroleum grease	Shielded	System test results nominal, lubricant not evaluated
Mobil Grease 28 - nonchanneling silicone grease	MTMs - shielded	System test results nominal, lubricant not evaluated
Rod end bearing - PTFE coated Nomex liner	D3 - exposed	Extensive test results were nominal

Table 3-1 Solid and Liquid Lubricants Flown on LDEF

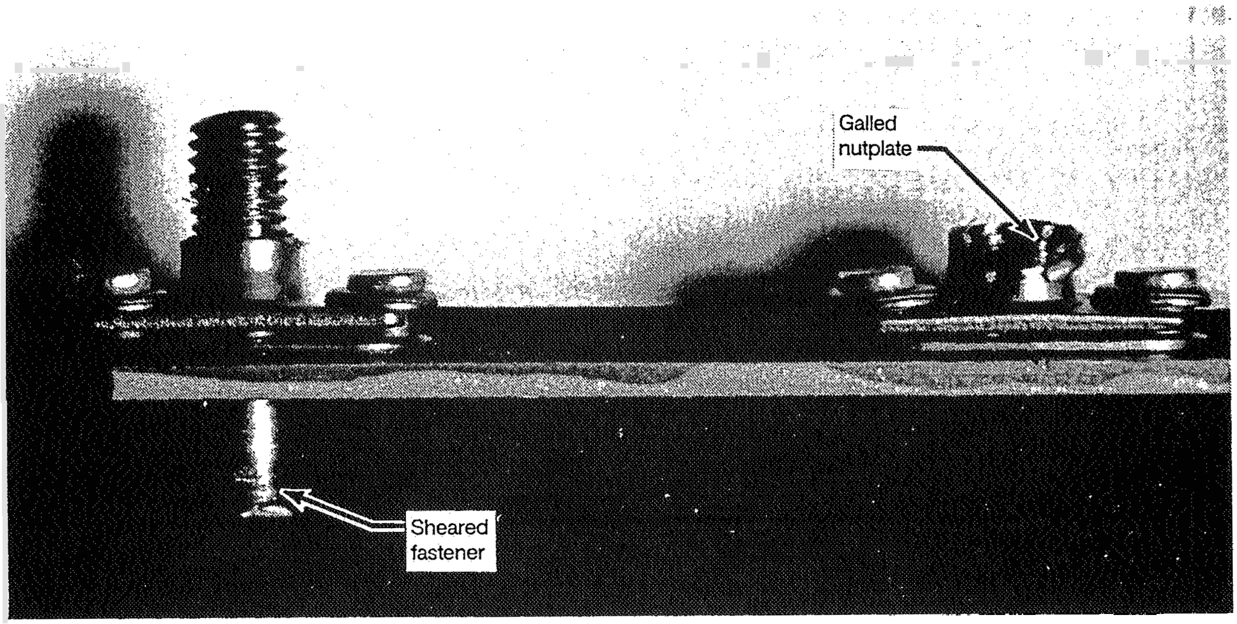


Figure 3.1-1. A Sheared fastener and a galled nutplate from Experiment AO175.

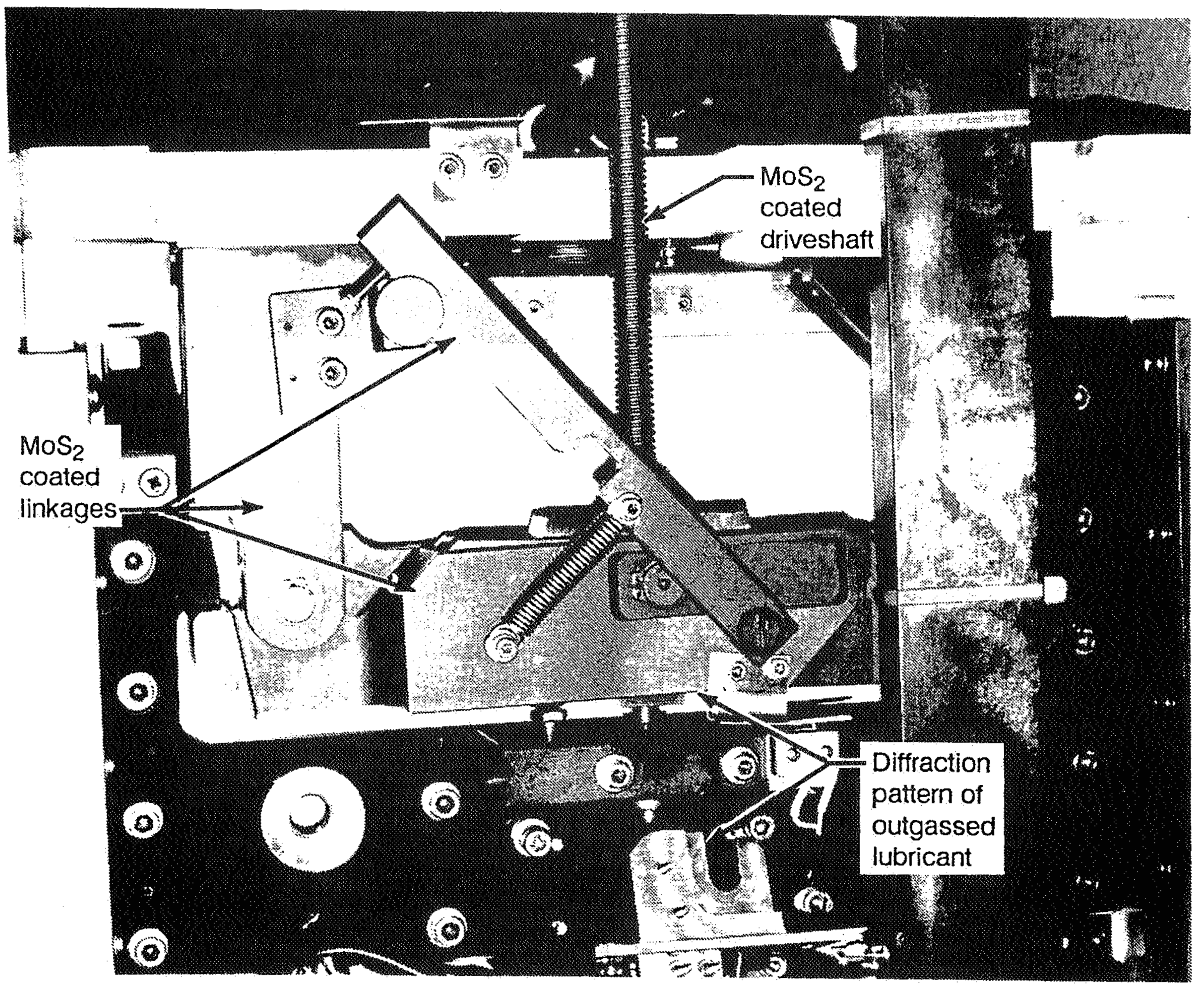


Figure 3.1-2. Location of MoS_2 on the backside of a EECC.

Visual inspection at up to 30X was performed and showed that the washers had several interesting features. As shown in figure 3.1-3, some of the washers concave surfaces appeared to have a buildup of lubricant at their perimeter, marked "B". These surfaces are where adjacent washers interface with each other. Next to this buildup, there was often an area devoid of lubricant, figure 3.1-3, area marked "A'. It is postulated that this condition was caused by displacement of the MoS_2 resulting from forces exerted on the lubricant from adjoining washers. Burnished areas, seen as the shiny area and marked "B" in figure 3.1-4, also existed where adjacent washers interfaced. No abnormal wear was seen. Areas where the dry film lubricant had thinned, often to bare metal, were present on some of the convex surfaces. **As** shown in figure 3.1-4, these surfaces had a similar appearance to the bare areas on the concave surfaces. No effects due to the 69-month exposure to LEO trailing edge environment were noted.

VacKote 18.07 and 21207

VacKote 18.07 and 21207, both made by Ball Aerospace, were used on carousel components of experiment S0069 on row 9 (leading edge). 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 590°F or 50 hours at 300°F). The 21207 is thin pure MoS_2 that contains no binder or glue and 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. No post-flight examination of the either lubricant has been performed.

MoS_2

Powdered MoS_2 was used on the opening/closing drive trains for the three canisters used on Experiment A0138 (located on the trailing edge, tray B3). The MoS_2 was applied by burnishing with a chamois skin and the excess was removed with clean paper. Post-flight inspection showed most of the exposed MoS_2 had been removed by exposure to UV and vacuum. MoS_2 remained on portions of the lubricated drive train shielded from UV but in less quantities as was on the ground control canisters. No pre-flight quantitative measurements were made so accurate erosion measurements were not possible (ref. 1).

Molykote Z and Vapor Deposited MoS_2

Dow Corning Molykote Z and vapor deposited MoS_2 was used on Experiment AOl38-10 (located on the trailing edge, tray B3). This static experiment consisted of stacks of 1 in-diameter washers machined from various metals that were representative of spacecraft mechanisms. The metals included aluminum alloys, copper alloys, titanium alloys, stainless steel, silver alloys, and palladium. Eight columns of six pairs of washers each (total of 48 washer pairs) were loaded together with various Belleville disc springs forcing contact pressures ranging from 4000 to 20,000 psi. Ground based control specimens were kept under vacuum during the 69-month' LDEF mission. Three of the washer pairs had one mating surface coated with Molykote Z and another three washer pairs had one mating surface coated with vapor deposited MoS_2. All eight columns of loaded washers were shielded from LDEFs exterior environment. The experiment's objective was to evaluate the tendency of various metals to coldweld and to determine the effect of MoS_2 lubricants on coldwelding. All flight and control specimens have been analyzed and no coldwelding occurred. No additional lubricant results have been reported. Additional experiment details are found in reference 2.

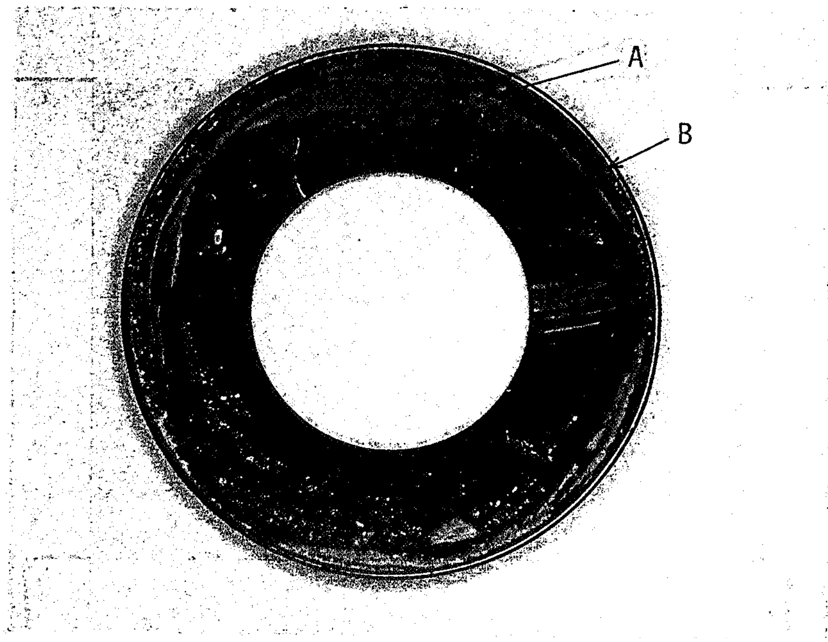


Figure 3.1-3. Concave surface of an EECC Belleville washer, showing area with no lubricant **(A)** and (B) lubricant buildup (3.2 **X** magnification).

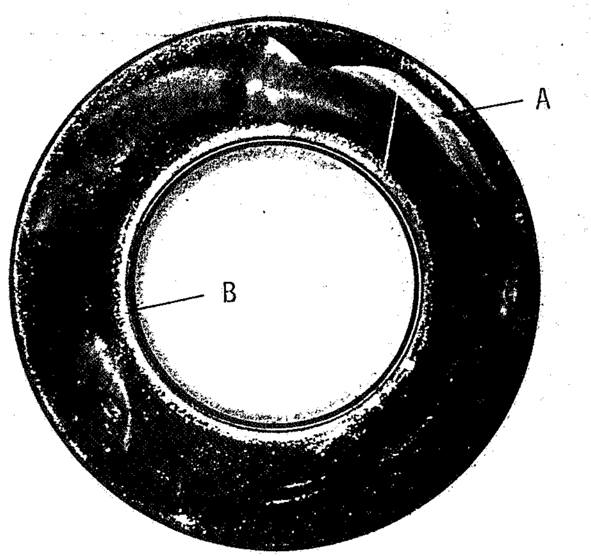


Figure 3.1-4. Convex surface of the washer shown in figure 3.1-3, showing area with no lubricant **(A)** and (B) burnished lubricant (3.2 **X** magnification).

Tungsten Disulfide

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 remote manipulator system (RMS) during (1) initiation of the active experiments using the rigidize sensing grapple and (2) deployment and retrieval of LDEF using the flight-releasable grapple. The grapples performed as designed. During post-flight analysis at Johnson Space Center, samples of WS2 were removed from both grapple shafts for Scanning Electron Microscope (SEM) and Energy Dispersion X-ray (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.

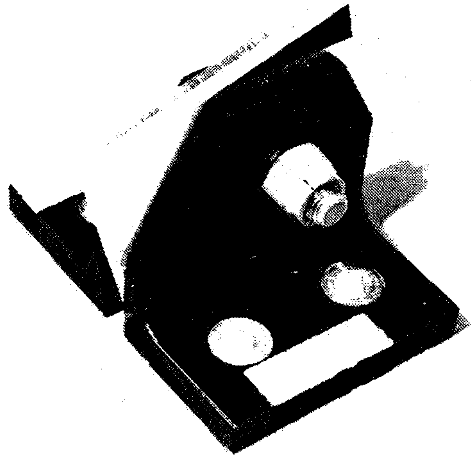
Silver-Plating

Silver-plating is used to prevent galling and seizure during both installation and removal of fasteners. The LDEF primary structure fastener assemblies consist of stainless steel bolts ranging in diameter from 1/4 to 7/8 in. with silver-plated locking nuts **(MS** 21046). All 2928 primary structure fastener assemblies were located on the interior of LDEF. Following completion of the experiment deintegration, all primary structure fastener assemblies were re-torqued to pre-flight values. Only 119 of the 2,928 (4%) assemblies had relaxed. Nut rotations required to reestablish pre-flight torque levels for those that relaxed ranged from 5 to 120 deg. An undisturbed, as-flown intercostal fastener assembly with a silver-plated nut is shown in figure 3.1-5. Cross-sections of the assembly were taken to determine the condition of the mating surfaces. Close-ups of these areas are shown in figure 3.1-6. Some minor galling and smearing of the silver-plating on the nut is evident and is considered normal behavior.

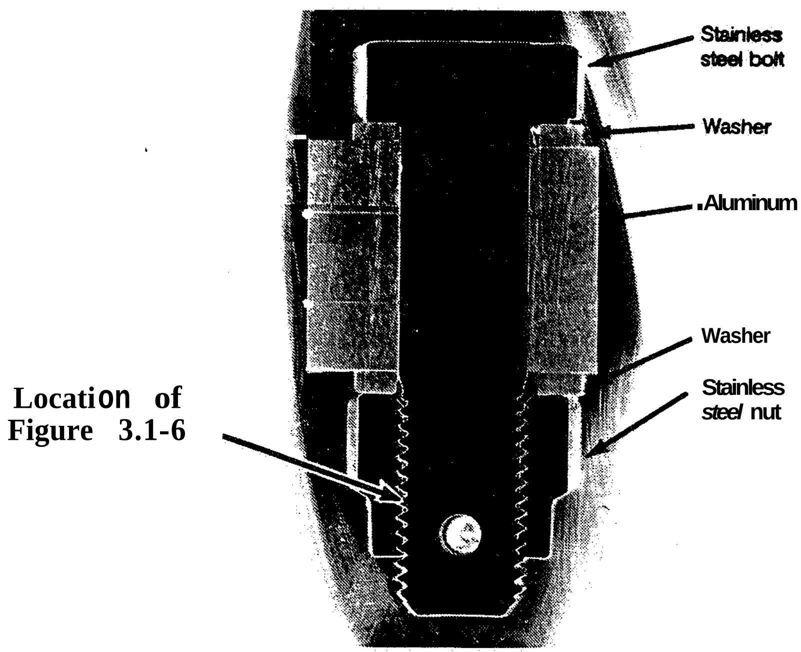
Twenty-four silver-plated nuts from LDEF intercostal clips were removed and analyzed. The nuts were removed from clips located on the inside of LDEF at the Earth and space ends. Two sizes of nuts were examined: 1/4 in. and 3/8 in. Analyses included FTIR, X-ray photoelectron spectroscopy, Auger electron spectroscopy, and photomicroscopy. Photographs of each nut were taken before any testing was done (figure 3.1-7). All exposed nut surfaces had a brown contaminant film. The color and distribution of this film varied between nuts and over the surface of each nut. There was no apparent correlation between the location of the nuts and the amount of film. It was initially speculated that the film was caused by oxidation of the silver-plating. However, the results from the analysis showed that the film was caused by deposition of molecular contamination, similar to deposits on other interior surfaces. The nuts had a deposition of silicone and silica/silicates from the decomposition of silicone, and of the amide material that may have originated from urethane paint. No degradation of the silver was observed. Several fasteners were cross sectioned and examined for wear. As can be seen in figure 3.1-8, all examined external surfaces appear nominal. *Silver-plating proved effective in maintaining pre-jlight installation torques during post-flight hardware removal.*

Vespel

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.



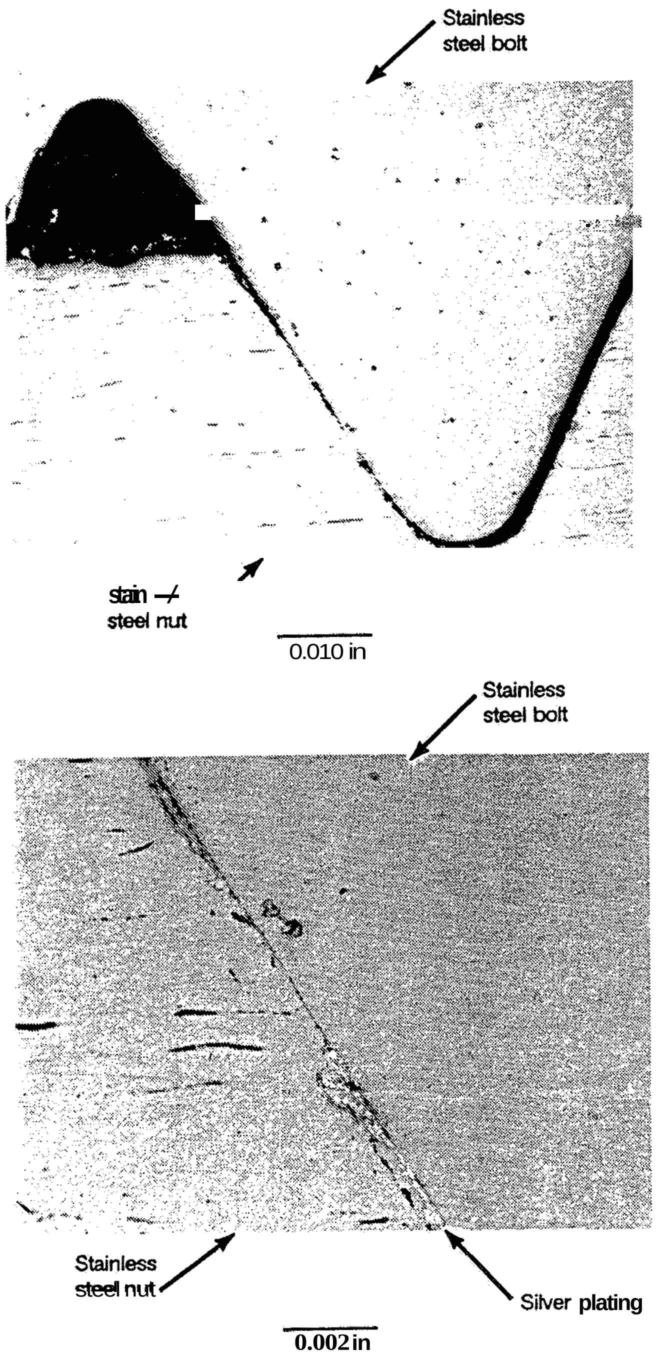
Fastener Assembly



Metallographic Cross-Section

0.040 in

Figure 3.1-5. Unassembled intercostal fastener assembly.



Intercostal Fastener Assembly Cross-Section

Figure 3.1-6. Close-up of nut/bolt thread interface of fastener shown in figure 3.1-5. Note smearing of silver-plating which acts as a lubricant between the nut and bolt.

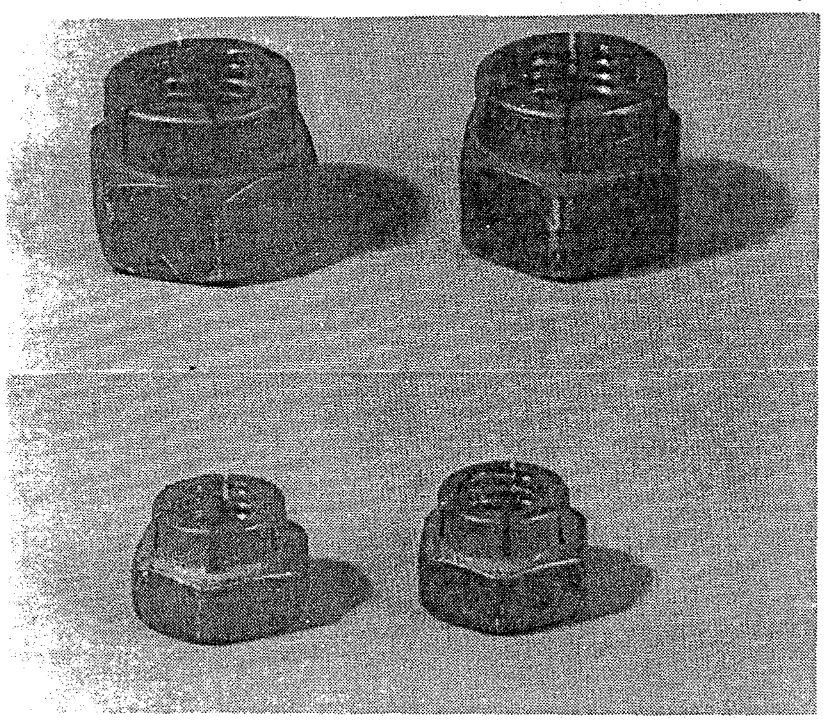


Figure 3.1-7. Photograph of silver plated nuts. All exterior nut surfaces had a brown contamination film, some more than others. Discoloration was not atomic oxygen caused oxidation. A color version of this figure is shown in "Analysis of Systems Hardware Flown on LDEF", April, 1992, page 292, (NASA CR 189628).

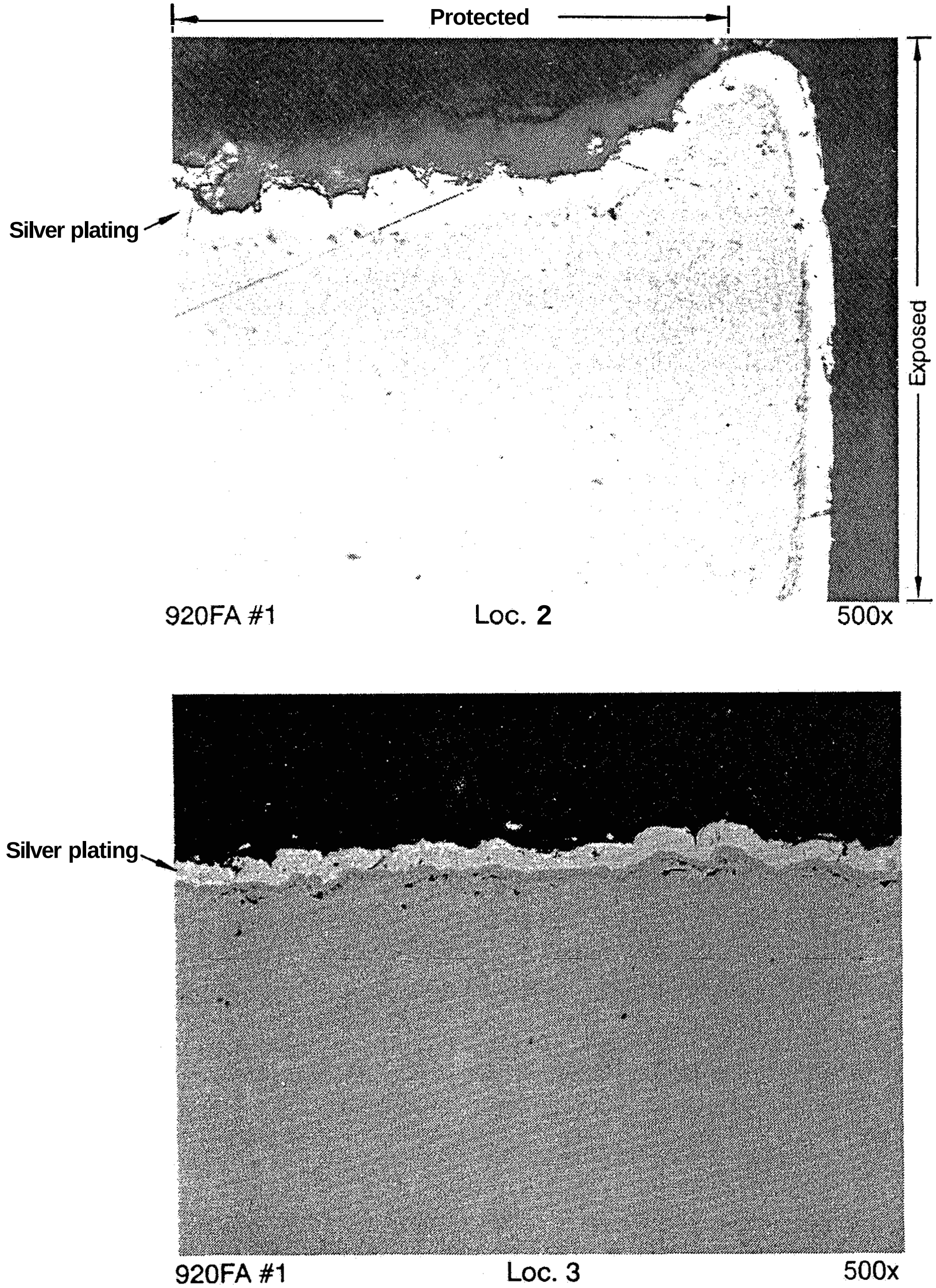


Figure 3.1-8. Cross **section of a silver plated nut.**

3.2 Solid Lubricants - Experiment Specimens

This section describes the results from testing of three solid lubricant systems and one bearing system that were flown as part of a Boeing materials experiment located on the exterior surface of the trailing edge (tray D3). These specimens were exposed to ≈ 11,000 equivalent sun hours but no atomic oxygen {ref. 3}. These were the only lubricants flown on LDEF that were experiment specimens. All other lubricants were functioning components of an experiment. Figure 3.2-1 is a deintegration photo of the tray D3 module that contained the Boeing lubricant specimens.

DuPont Vespel SP-21

Vespel SP-21 is a machinable DuPont product of polyimide resin filled with 15%, by weight, graphite. As shown in figure 3.2-1, this material was flown as four 0.5" diameter buttons. Two flight specimens and two control specimens were tested on Boeing's high load friction and wear test machine in a standard test lab environment. The friction and wear test machine is capable of testing four pairs of specimens at one time. The four 0.5" diameter Vespel buttons were cycled against four 1" x 2" 17-4 stainless steel plates. These plates were spherically mounted insuring that the plate load was normal to the button. The test results, shown graphically in figure 3.2-2 (table 3-2 contains the raw data), indicated that no changes in lubricity had occurred and that the long term exposure to UV did not degrade the Vespel SP-21. Optical and EDX comparison (figure 3.2-3) of the flight specimens (before friction and wear testing) with control specimens also showed no differences.

DuPont Vespel SP-211

Vespel SP-211 has 10% Teflon resin and 15 % graphite, by weight, added to the base phenolic resin to provide a low coefficient of friction over a wide range of operating conditions. This material was also flown as four 0.5" diameter buttons and were located next to the Vespel SP-21 buttons in figure 3.2-1. Comparison of the flight specimens with control specimens showed no differences.

Everlube 620C (MIL-L-8937)

Initial review of pre-flight documentation led us to believe that six 0.5" dia x 0.25" thick 17-4 PH stainless steel buttons had been initially coated with Everlube 620C. Post-flight testing and analysis determined that no 620C existed on the 0.5" dia buttons. LDEF experiments were assembled in the late 1970s which has made documentation of pre-flight details of each specimen difficult. The apparent loss of 620G was reported to the LDEF community in several reports and presentations. However, more detailed examination of pre-flight documentation and pre-flight photos provided by The Aerospace Corporation show that the 0.5" buttons were never coated with Everlube 620C.

Polytetrafluoroethylene (PTFE)-Coated Nomex/Rod End Bearings

Three rod end bearings, qualified to MIL-B-81820, were also flown on tray D3 (see figure 3.2-1 for location). Two of the three bearings were sent to New Hampshire Ball Bearings (original manufacturer) for testing and comparison to original specifications. Figure 3.2-4 is a typical side view of a LDEF bearing. Also shown is an "off the shelf' comparison bearing on the right. Appendix C is the 40 page New Hampshire Ball Bearings test report. The following three paragraphs summarize the findings.

The peel strength needed to remove the PTFE-coated Nomex liner from the bearing body was determined. The liner system consists of a porous Teflon membrane embedded in a Nomex open weave cloth using a phenol formaldehyde thermosetting resin. The specification specifies a minimum peel strength of 2 lbs/in. The LDEF specimen tested recorded an average peel strength of 3.8 lbs/in and the "off the shelf' comparison specimen recorded an average peel strength of 2.6 lbs/in. Figure 3.2-5 shows the comparison peel

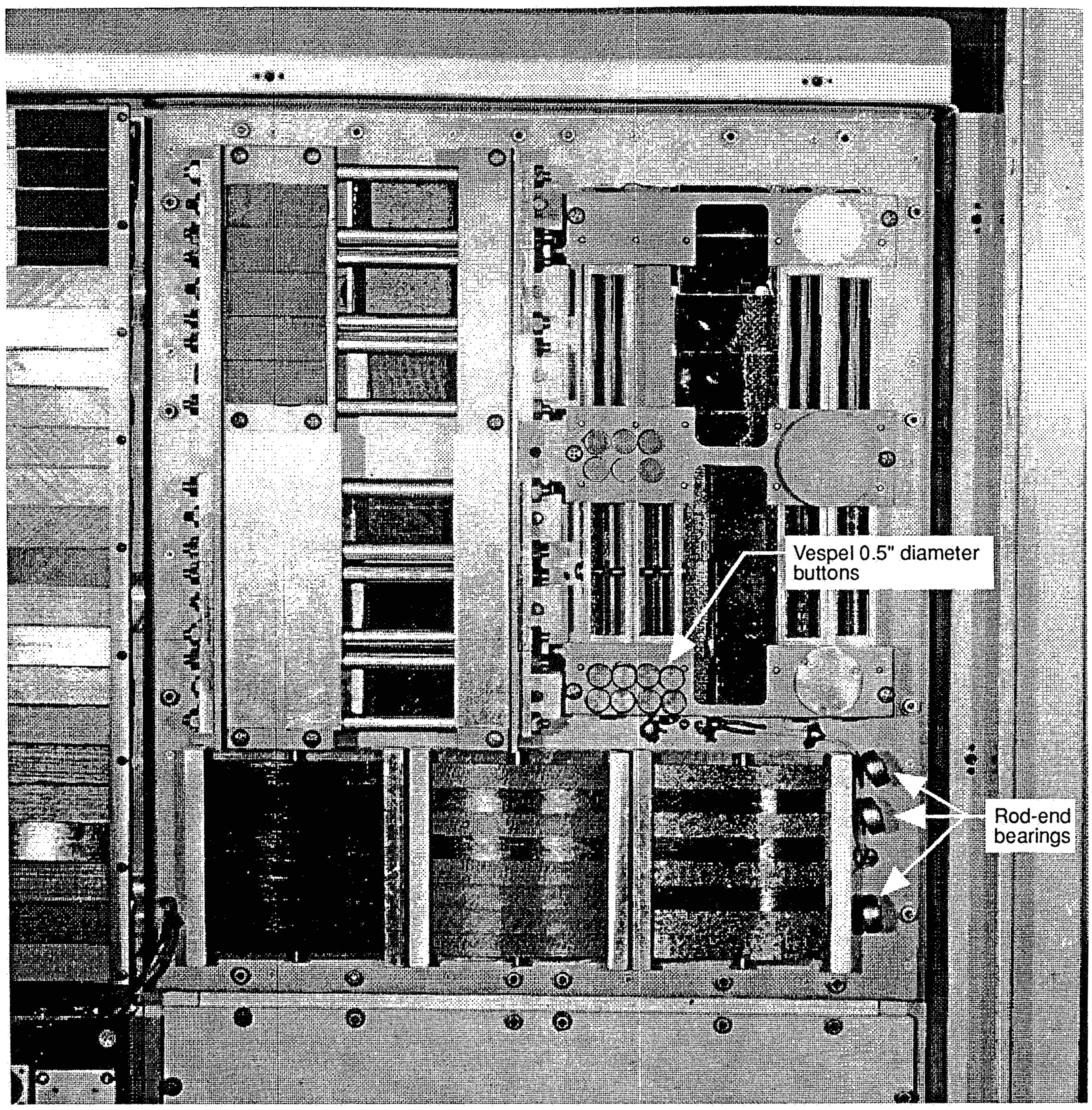


Figure 3.2-1. Deintegration Photo of Tray D3 Module Showing the Location of the Vespel and PTFE-coated Nomex Rod-end Bearings.

105830Job1-1

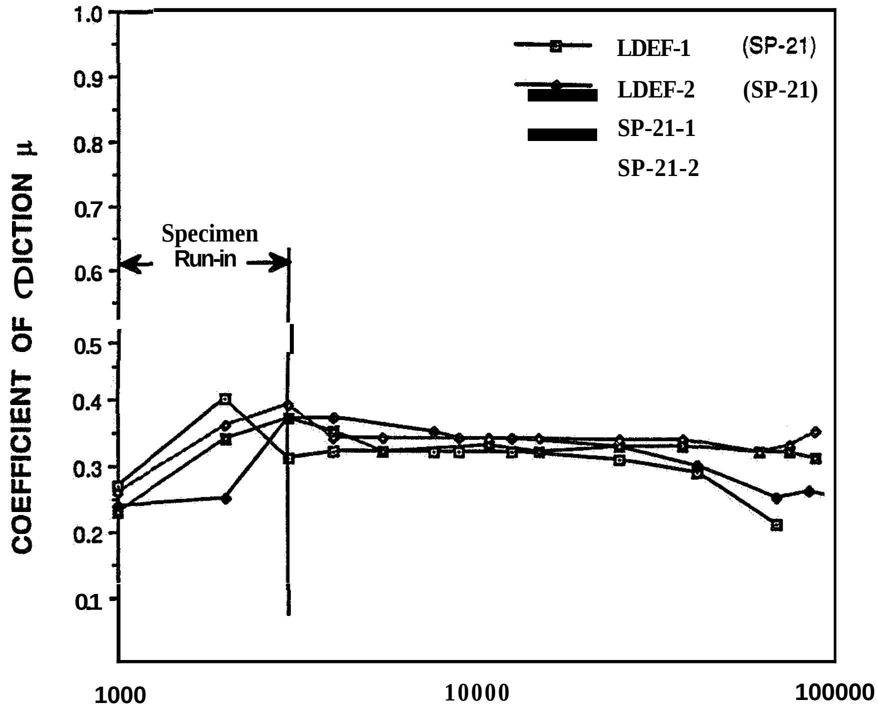
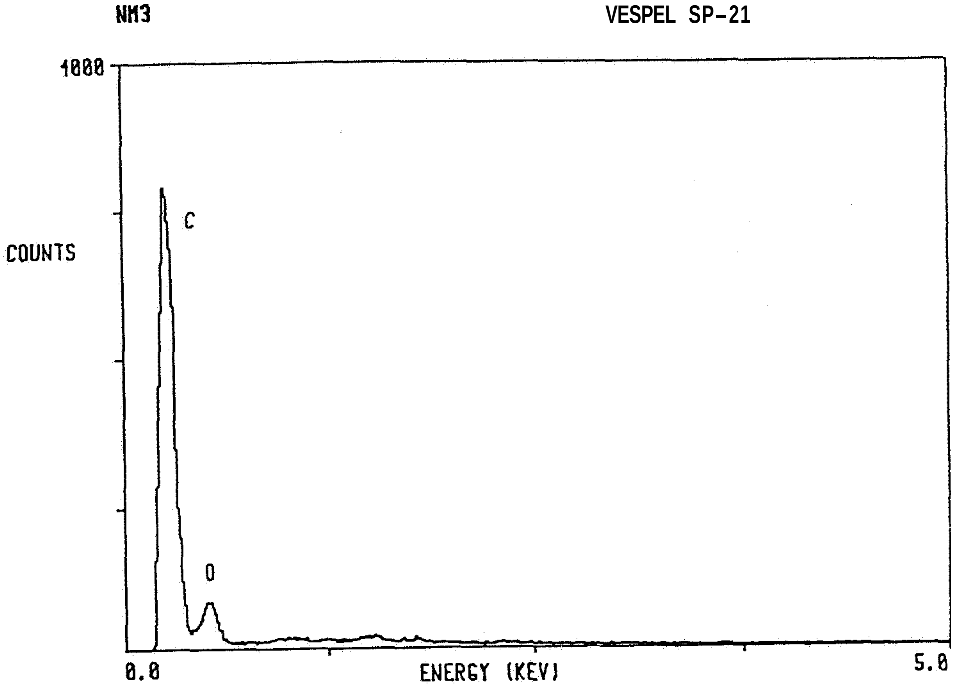


Figure 3.2-2. Vespel SP-21 friction test results. Specimen run-in consisted of pressure-velocity values of the friction and wear test machine increasing slowly from 3,125 to 25,000 over the first 3,000 cycles.

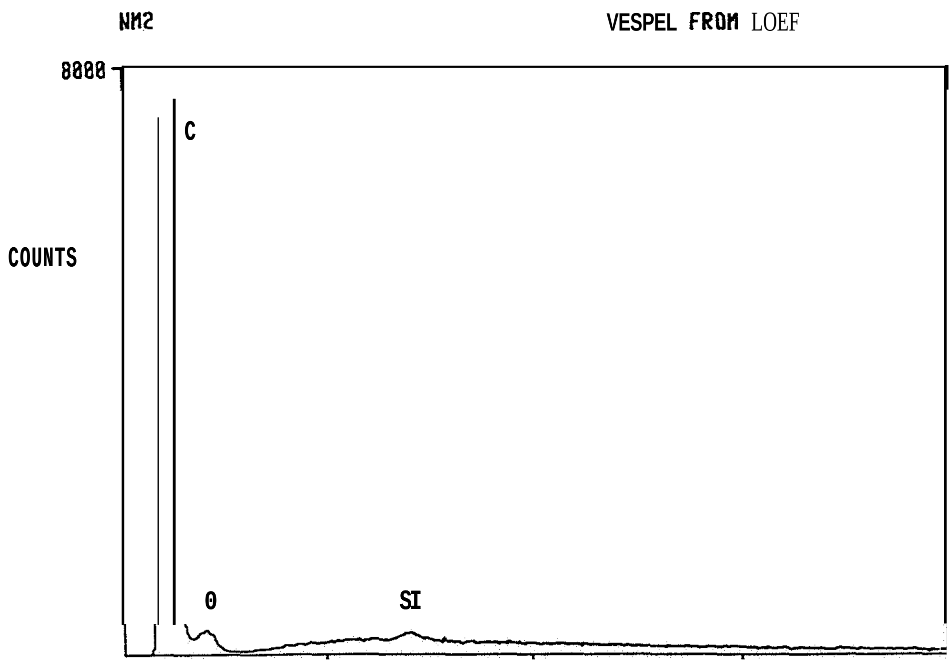
VESPEL SP-21 FRICTION DATA (Tested unlubricated in air at room temperature)					
Cycles	Pressure x velocity (Psi*ft/min)	Coefficient of Friction			
		LDEF-1 Flight specimen	LDEF-2 Flight specimen	SP-21-1 Control specimen	SP-21-2 Control specimen
0	3,125	0.27	0.24	0.24	0.25
1,000	6,250	0.27	0.24	0.23	0.26
2,000	12,500	0.40	0.25	0.34	0.36
3,000	25,000	0.31	0.37	0.37	0.39
4,000	25,000	0.32	0.37	0.35	0.34
5,500	25,000			0.32	0.34
7,600	25,000	0.32	0.35		
9,000	25,000	0.32	0.34		
10,800	25,000			0.33	0.34
12,600	25,000	0.32	0.34		
15,000	25,000			0.32	0.34
17,000	25,000				
22,000	25,000				
25,400	25,000	0.31	0.33	0.33	0.34
30,000	25,000				
38,000	25,000			0.33	0.34
41,500	25,000	0.29	0.30		
58,000	25,000				
62,300	25,000			0.32	0.32
65,000	25,000				
69,200	25,000	0.21	0.25		
71,000	25,000				
75,000	25,000			0.32	0.33
85,000	25,000		0.26		
100,000	25,000		0.25		

* First 3.000 cycles are run-in period with increasing PV each 1000 cycles.

Table 3-2. Vespel SP-21 data used to create Figure 3.2-2.



VESPEL SP-21 BASELINE SAMPLE
(EDX scan on the electron microscope)



VESPEL SAMPLE FROM THE LDEF
(EDX scan on the electron microscope)

Figure 3.2-3. EDX comparison of a Vespel 21 coupon flown on LDEF and a control specimen.

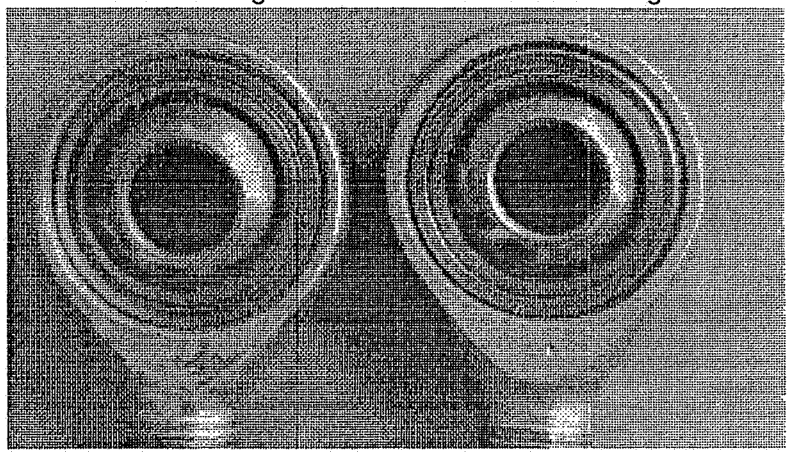


Figure 3.2-4. Side View of a Rod-end Bearing Flown on LDEF and a Similar Off-the-shelf Bearing.

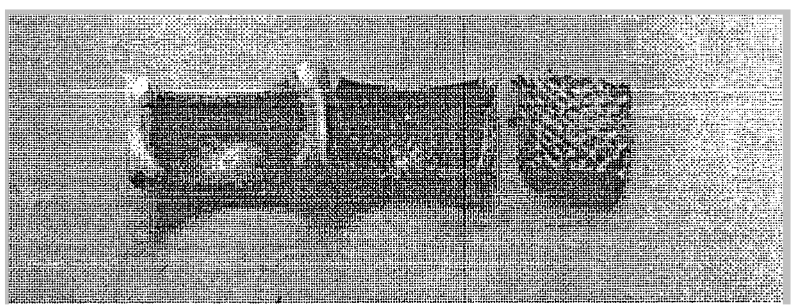


Figure 3.2-5. Control Rod-end Bearing Peel Test Specimen Showing the Liner Face, Liner Adhesive Bond Interface and the Rear Surface of Peeled Liner.

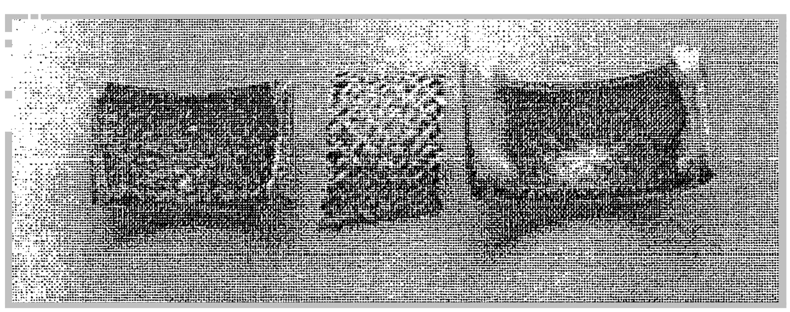


Figure 3.2-6. LDEF Rod-end Bearing Peel Test Specimen Showing the Liner Face, Rear Surface of Peeled Liner and Liner Adhesive Bond Interface.

strength specimen and figure 3.2-6 shows the LDEF specimen. Both photos show the liner wear surface, the rear of the liner surface and the glue line retained on the race. Inspection of the Nomex/PTFE liner showed no degradation.

Preload torque tests showed no increase when compared to similar "off the shelf" bearings. Oscillating load testing was performed by applying a unidirectional load to the bearing, oscillating it at ±25 degrees at 20 cycles/min for a total of 25,000 cycles, at which time the allowable wear requirement is less than 0.0039 inches. Results of the oscillating load testing showed the wear rates were approximately 80% of the wear rate allowable. While the LDEF specimen wear rates were within the allowable rate specified in MIL-B-81820, they exhibited twice the wear rate of a similar "off the shelf" bearing.

The exterior surfaces of the bearing bodies were cadmium-plated in accordance with Federal Specification QQ-P-35, Class **2,** Type 11 (cadmium-plating is generally prohibited for space use because of its high vapor pressure and hence the potential for contamination of optical and other critical surfaces). The Type II designation requires that the parts receive a chromate conversion coating after cadmium plating. The conversion coating, which was an iridescent yellow brown color, exhibited signs of degradation (as shown in figure 3.2-4). 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. **As** has been observed with the aluminum conversion coatings used on LDEF, the hexavalent chromium in the conversion coating may have been reduced to trivalent with the associated loss of color. No changes in the cadmium plating were noted.

3.3 Liquid Lubricants

Apiezon H

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. In an attempt to determine the effects of the 69-month exposure to vacuum on Apiezon H, specimens were tested for outgassing in accordance with NASA SP-R-0022A. The initial total **mass** loss (TML) and condensible volatile collectable materials (CVCM) testing was performed 3 months after LDEF' s return to the Earth atmosphere. As shown in table 3.3-1, this initial 7-day test of an Apiezon H flight sample had considerably higher TML than the control sample but the CVCM was similar (the control material was 1990 off-the-shelf material provided by the manufacturer). It was postulated that this was due to the LDEF sample picking up moisture between satellite retrieval and sample test. Therefore, a series of additional TML and CVCM tests were performed to determine the propensity of Apiezon H to absorb atmospheric moisture (Appendix D-2 through D-7 contains the Apiezon H outgassing data sheets). A thin film of grease was exposed to 100% humidity at room temperature prior to testing. The absorbed moisture resulted in a TML 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. Per information supplied by the manufacturer, Apiezon greases demonstrate good gettering properties meaning they will adsorb impurities, including water vapor, until an equilibrium level is reached. The data shown in table 3.3-1 agree with the known gettering properties of Apiezon H. This data, along with the chemical analysis, implies that changes noted in the Apiezon H flown on LDEF were caused by the post-flight storage on Earth, not by the 69-month exposure to LEO vacuum environment. The thermal stability of Apiezon H has changed over the years per the NASA Goddard Space Flight Center (GSFC) data, also shown in table 3.3-1.

SAMPLE ID	TEST DURATION	DAYS TEST OCCURRED AFTER LDEF RETRIEVAL	TOTAL MASS LOSS (%)*	VOLATILE CONDENSIBLE MATERIAL (%)*
LDEF	7 days	≈ 95	2.32	0.66
Control	7 days	NA	0.97	0.58
LDEF	1 day	≈180	1.42	0.44
Control	1 day	NA	0.53	0.18
Control with 2 days humidity	1 day	NA	0.72	0.21
Control with 21 days humidity	1 day	NA	1.38	0.25
Goddard Test Data (1973 data)	1 day	NA	0.25	0.02
Goddard Test Data (1993 data)	1 day	NA	1.21	0.54

* All data is the average of two specimens

Table 3.3-1 Apiezon H Outgassing Data

Apiezon L

Apiezon L was used on experiment A0180 as a lubricant to ensure successful post-flight removal of fasteners. Post-flight fastener removal was completed with no difficulties. No lubricant related testing was performed on Apiezon L used on LDEF. However, table 3.3-2 shows outgassing data performed at Boeing and at NASA Goddard Space Flight Center on "off the shelf" Apiezon **L** showing trends similar with the Apiezon H grease testing (Appendix D-8 through D-10 contains all the Apiezon L outgassing data sheets) **.**

SAMPLE ID	TEST DURATION	TOTAL MASS LOSS (%)*	VOLATILE CONDENSIBLE MATERIAL (%)*
Control	1 day	0.08	0.04
Control	7 days	0.21	0.15
Control with 2 days humidity	1 day	0.76	0.04
Goddard Test Data	1 day	0.04	0.01

* All data is the average of two specimens

Table 3.3-2 Apiezon L Outgassing Data.

Apiezon T

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 44177

Ball Brothers lubricant 44177 was used to lubricate the thrust washer on the five EECCs. A nearby bracket was found to have a diffraction pattern due to the outgassing of the volatile component of the lubricant as shown in figure 3.3-1. Although the 44177 is still used on previously designed spacecraft, Ball Brothers no longer recommends it for new designs.

Braycote 601

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 Braycote 601 saw an insignificant fluence of atomic oxygen. The lubricant had changed to a black color which is thought to be some form of unidentified contamination. Castrol 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. Thermogravimeteric analysis results of the flight sample are very similar to those of a control sample. Slight differences were 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.

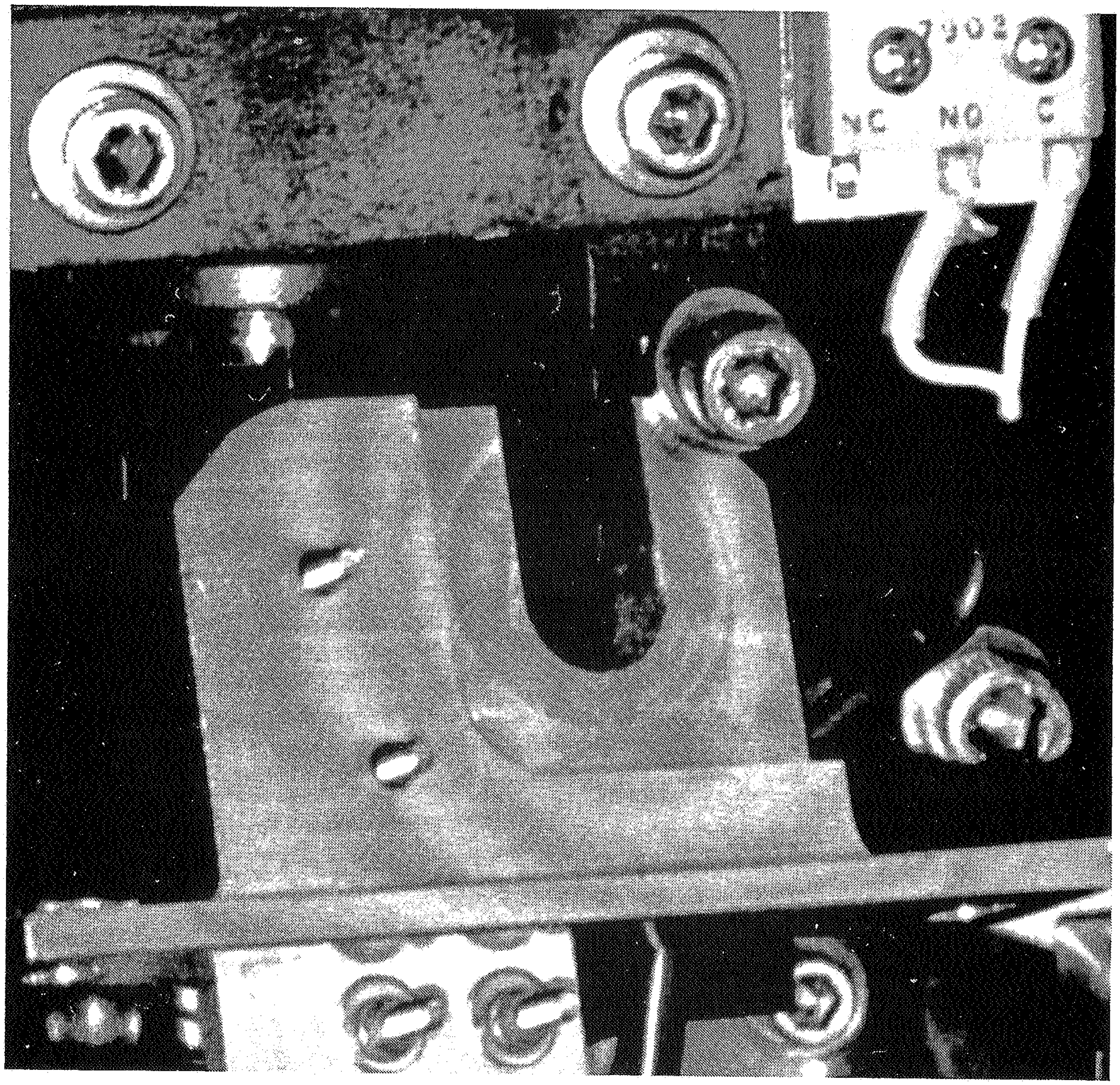


Figure 3.3-1. Diffraction pattern of the Ball Brothers 44177 lubricant,

Mobil Grease 28

Mobil Grease 28 was used on the seven NASA provided magnetic tape modules (MTM). The MTMs contained the cassette tape that recorded on-orbit data. The MTM bearings contained 25% grease fill. The bearings along with the rest of the MTM hardware were contained within an Viton O-ring sealed enclosure that was backfilled with 95% nitrogen and 5% helium. The MTMs were tested and compared to pre-flight measurements. No significant changes in wow/flutter and tracking were noted. The MTMs were not disassembled, therefore, no grease analysis has been performed. However, no changes in the grease would be expected as it was in a sealed enclosure backfilled with an inert atmosphere.

Dow Corning 340

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 atomic oxygen. 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

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

Exxon Andok C was used in Experiment S0069, Thermal Control Surfaces Experiment. No post-flight testing has been performed.

4.0 SEALS

Table 4-1 identifies the variety of seals used on LDEF. With the exception of the ethylene propylene diene monomer rubber (EPDM) and acrylonitrile butadiene rubber (NBR) specimens evaluated in Experiment P0005, all seals were functioning components of various experiments. Most of these seals were O-rings although sheet rubber was also used. In addition, materials that are commonly used for seals were used as cushioning pads. Unless noted, all seals were shielded from the exterior LDEF environment, preventing exposure to the potentially degrading atomic oxygen and/or solar UV environments. All seals and seal materials sustained little or no degradation caused by the long term exposure to LEO. The performance of the seals flown on LDEF are discussed in the following paragraphs.

ELASTOMERIC PARTS	LDEF EXPERIMENT	COMMENTS
Butyl O-ring	P0004	1,3
Butyl rubber seal	EECCs A0138	1,3 1,3
EP O-ring	S0069, S1005	3
EPDM rubber	P0005	1,3
NBR rubber	P0005	1,3
Neoprene gasket	A0139	1
Nitrile O-ring	M0006	1
Silicone gasket	S0050	1,2,3
Silicone pad	M0004	1,2,3
Viton O-ring	A0015, A0134, A0138-2, A0139, A0180, M0001, M0002, P0005, S0010, S0069	1,3
Viton washer	A0189	1,3
Metal "V" washer	EECCs	1,3

Key to Comments: 1 - Performed as expected
2 - Discolored where exposed to UV
3 - Results discussed in this paper

Table 4-1 Seals Flown on LDEF.

Butyl 0-Rings

Butyl O-rings were used in face seals on LDEF Experiment P0004. 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 seals were as expected.

Butyl Seals - EECC

Butyl seals (Parker seal B-612-70) were used to seal the drawers on the five EECCs flown on LDEF. The EECC is essentially a sealed drawer in which small samples were mounted for controlled space exposure. Typically the canisters were programmed to open 10 days after deployment and close one week prior to the originally anticipated retrieval of LDEF (day 297). The drawer was opened by a screw drive actuator driven by an 28V DC electric motor (figure 3.1-2 shows the backside of an EECC and the MoS_2 coated driveshaft). The butyl seal was used to seal the drawers. Except for the 9 months the drawers were open, the seals were shielded from the external spacecraft environment. Table 4-2 shows the post-flight canister pressures just prior to opening, canister leak rates, and days after retrieval the canisters were opened.

Leak rates were determined for three of the five canisters. The measured post-flight leak rates were obtained by pumping the EECC down to approximately 1 Torr and then measuring vacuum levels the following day. The trailing edge canister had an initial 24 hour leak rate of 2.7 Torr compared to leak rates for the leading edge or near leading edge canisters (tray B9 and D8) of over 12 Torr/24 hours. Typical pre-flight leak rates for the canisters were around 1.3 Torr/24 hours. The cause of increased leak rates for tray B9 and D8 EECCs is unknown. However, it is unlikely the higher leak rates were caused by atomic oxygen degradation of the seal's performance following 9 months of exposure (the seals were shielded after the EECCs closed on day 297). The leading edge atomic oxygen fluence level for the first 9 months of LDEFs mission was approximately 2.3×10^{20} atoms/cm^2 (2.6% of the mission's total leading edge atomic oxygen fluence, ref. 3). It is unlikely this low fluence degraded the seal's performance. In addition, it was observed with the aid of the helium leak detection equipment, that the lower corners of the D8 EECC drawer seal were the areas of leakage. Further, it was noted that the D8 & B9 canisters showed heavy dark brown stains where as the D4 canister on the trailing edge had much lesser deposits. Debris were noted on the lower corners of the D8 drawer seal in the area of the detected leaks. This suggests the outgassing contaminants might have interfered with resealing of the drawers after the 9-month exposure.

While unable to obtain detailed pressure and leak measurements, the S1002 experimenters noted that no pressure differential between the canister and atmosphere was apparent at the time of opening.

Experiment #	LDEF Locations (tray #)	Pressure prior to opening (Torr)	Measured leak rate (Torr/24 hrs)	Days EECC opened after LDEF returned to Earth
M0006	C3 (trailing edge)	< 1 atm	2.7	60
S0010	B9 (leading edge)	≈ 1 atm	12.3	102
S1002	E3 (trailing edge)	1 atm	-	122
M0003	D8 (off-leading edge)	1 atm	12.6	149
M0003	D4 (off-trailing edge	≈ 300	-	150

Table 4-2 EECC Butyl Seal Performance Data.

Butyl Seals - A0138

The Butyl seals used to ensure vacuum inside of the three canisters flown on experiment A0138 (tray B3) underwent post-flight characterization. Each of the three seals were bonded to one of the face-plates of the canisters as shown in figure 4-1. 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 on-orbit open position, which was the first 10 months of LDEFs mission, the seals were protected from direct exposure to the trailing edge environment by an aluminum shield. Two tests were performed on the flight and control seals; micro-hardness and compression set (22 hours, 212°F and 25%). The 4% increase in micro-hardness indicated a slight aging of the butyl as confirmed by the decrease in compression set. The experimenter concluded that the seals were still in good working order and efficiently adhered to the canisters (ref. 4).

	Hardness*	Compression set (%)
- Flight model B3	55	5.5
- Reference model B6	53	8.3

* International Rubber Hardness Degrees (IRDH)

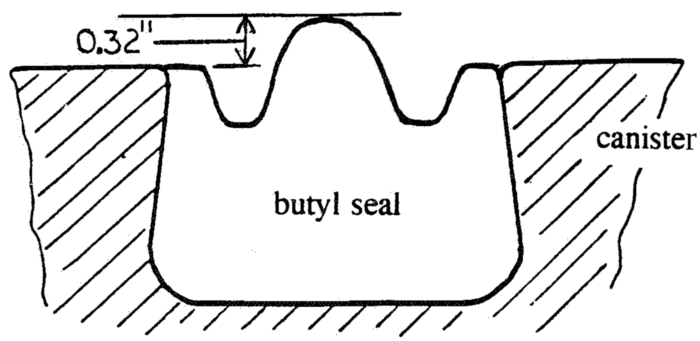


Figure 4-1. Schematic of the FRECQPA canister butyl seal.

Ethylene Propylene

Ethylene propylene (EP) O-rings were used to seal the ten lithium carbon monofluroride (LiCF) battery boxes used on NASA Marshall Space Flight Center's (MSFC) two active experiments, SO069 and S1005. During deintegration of the two experiments it was noticed that all 10 LiCF batteries had a strong odor. The electrolyte used in these Eagle-Picher LiCF batteries is dimethyl sulfite, which contains small amounts of other sulfur compounds that can be quite odorous. **AZ** Technology investigated the effect of the leaked electrolyte vapors on the EP O-ring seal of the battery containment case (ref. 5). The presence of this strong odor was determined to be the normal byproduct of the discharge process. The LiCF cell is designed with **an** expansion diaphragm on the top of the cell with a sharp, rigid protrusion adjacent to the diaphragm. Figure 4-2 is a close-up of one of the LiCF cells showing the expansion diaphragm. The diaphragm expanded during the slow discharge process when internal cell pressures increased. Eventually the diaphragm was punctured, releasing the solvent vapors. The cells were in the EP O-ring sealed battery boxes. The EP seal experienced softening and deformation due to the extended exposure to the electrolyte vapors which resulted in leakage of the vapors outside of the battery box. These seals failed due to excessive compression set of the O-rings. However, this created no performance problem for the battery or associated equipment. Figure 4-3 shows cross-sections of a control O-ring and a flight O-ring. Since the temperatures experienced by the batteries, 55 to 80°F, are well within the limits of EP material capabilities, the failure has been attributed to attack of the O-ring by the battery electrolyte, dimethyl sulfite. Since this same failure occurred on the ground-stored control batteries, the failure was not caused by exposure to the LEO environment.

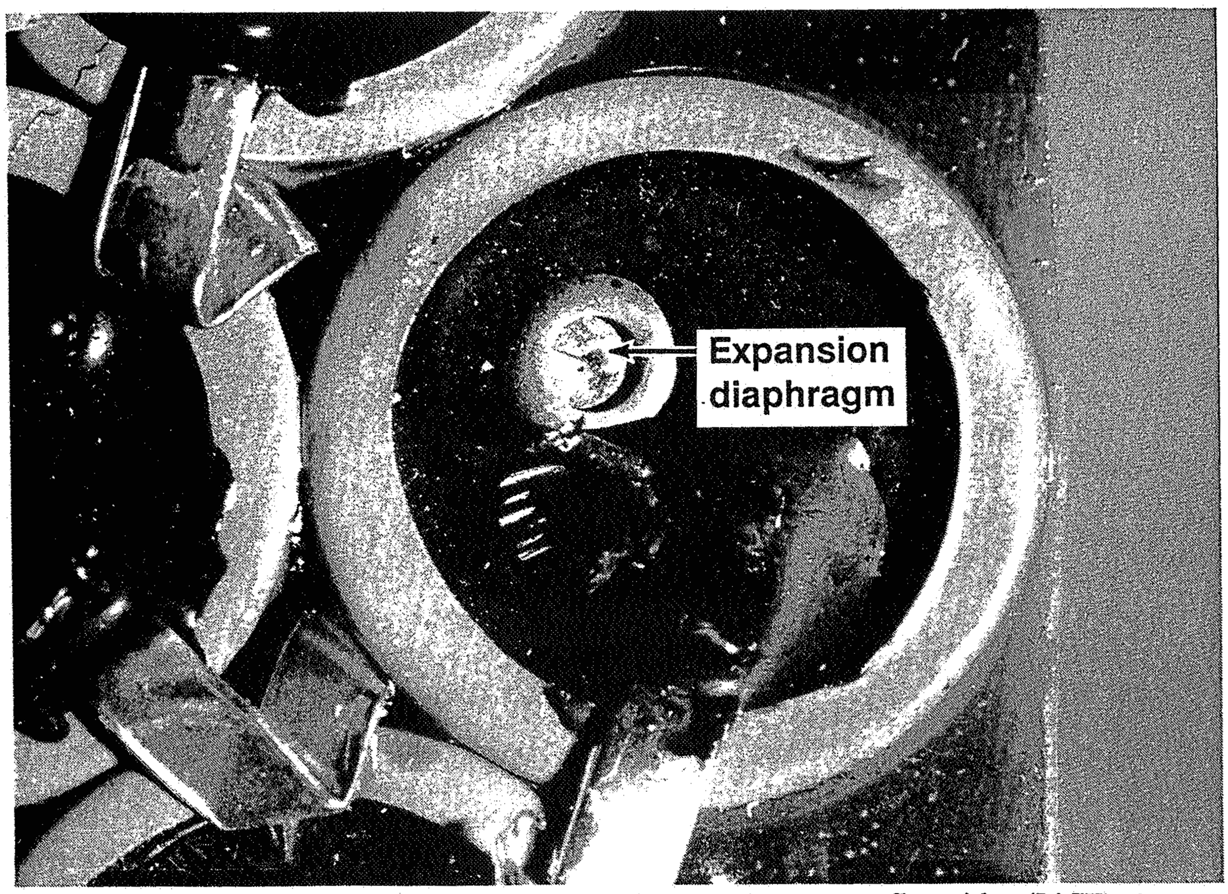


Figure 4-2. Expansion diaphragm of a lithium carbon monofluroride (LiCF) battery cell.

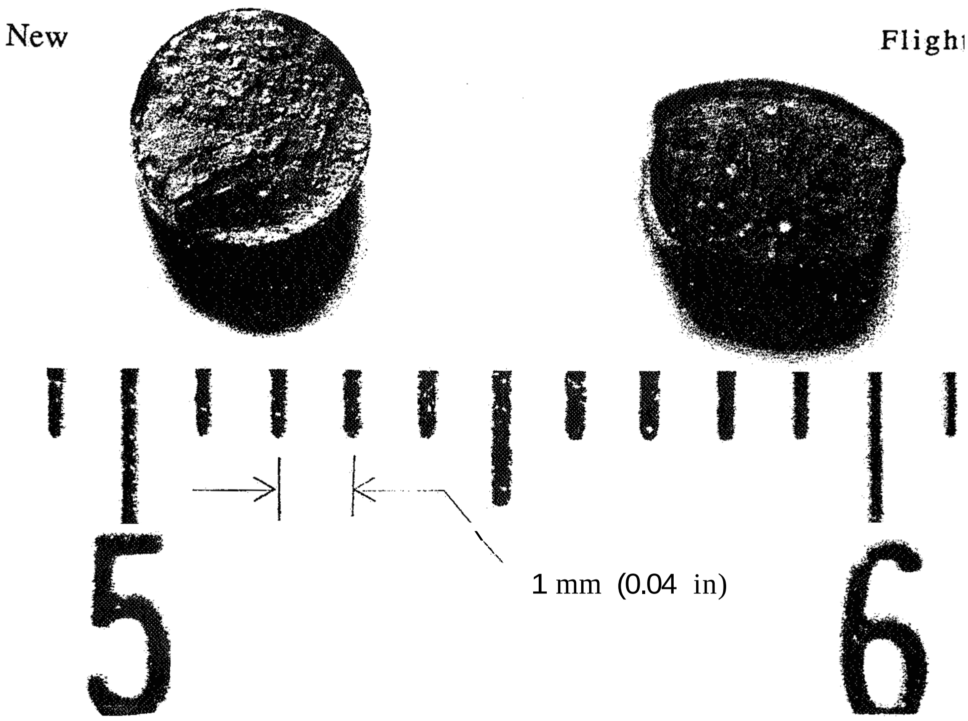


Figure 4-3. Control O-ring vs O-ring used on LiCF batteries flown on LDEF.

An EP O-ring, shown in figure 4-4, was used to prevent leakage of the viscous damper silicone oil at the fill-port plug of the magnetic damper. General Electric Astro Space Division was funded by Lockheed Engineering and Sciences Co. to determine the post-flight evaluation of the damper (ref. 6). This post-flight investigation included an extensive evaluation of the fill port EP seal. Visual examination of the flight O-ring showed no evidence of degradation, distortion, flat spots, loss of flexibility or swelling. No dimensional changes in cross-section or internal diameter were found. Scuff marks were found but probably resulted from the tightening of the fill-port plug and did not represent deterioration of the O-ring. Hardness testing showed the flight O-ring to possess a hardness of 65 durometer. The pre-flight hardness was likely 60 or 70 durometer hardness, but because of ambiguity in the material call-out on the O-ring drawing, the exact pre-flight hardness is unknown. General Electric Astro Space concluded no degradation occurred in the O-ring.

EPDM and NBR

The following two seal materials were tested on Experiment P0005; (1) EPDM with a silica filler and a sulfur cure and (2) NBR that was silca/asbestos filled and also sulfur cured (ref. 7). Three ASTM Die C dog bone specimens of each material were flown on LDEF. These two seal/insulation materials were selected as being representative of materials used in the fabrication of solid rocket motor assemblies. The materials were packaged (along with other solid rocket motor materials) within a 5" x 6" x 11.5" aluminum container and attached to an interior plate on LDEF's center ring. The container was flushed with dry nitrogen and sealed prior to installation on LDEF. An air pressure activated valve was designed to vent the box when it was subjected to a pressure below 0.2 atm, leaving the box open to vacuum. On re-entering, the valve was designed to close at 0.5 atm external pressure keeping the specimens in vacuum until post-flight testing. Control specimens were also kept in nitrogen during the entire 69-month LDEF mission.

During deintegration of the experiment at Morton-Thiokol, it was determined that the aluminum container was at atmospheric pressure. Apparently a slow leak had developed within the container which allowed the contents of the container to slowly arrive at atmospheric pressure following the return of LDEF. However, it was also determined that the valve had initially opened as designed exposing the specimens to vacuum for the 69-month mission. Post-flight weight loss measurements were taken approximately 2 months after LDEFs return. The weight loss data for the EPDM and NBR (shown in table 4-3) showed an average weight loss of 1.4% for the EPDM and 0.8% for the NBR. The principal investigator suggests that these results may be due to loss of water from the EPDM and a loss of volatile plasticizer from the NBR, based on the loss of strain capability in the NBR (shown in table 4-4 and figure 4-5).

SAMPLE	INITIAL WT	POST-FLIGHT WEIGHT	PERCENT CHANGE
EPDM #1	5.1829	5.1072	-1.46
EPDM #2	5.1461	5.0739	-1.40
EPDM #3	5.1079	5.0380	-1.37
NBR #1	1.1197	1.1126	-0.63
NBR #2	1.1868	1.1768	-0.84
NBR #3	1.1941	1.1822	-1.00

Table 4-3. Weight Loss Data for EPDM and NBR flown on P0005 (ref. 7).

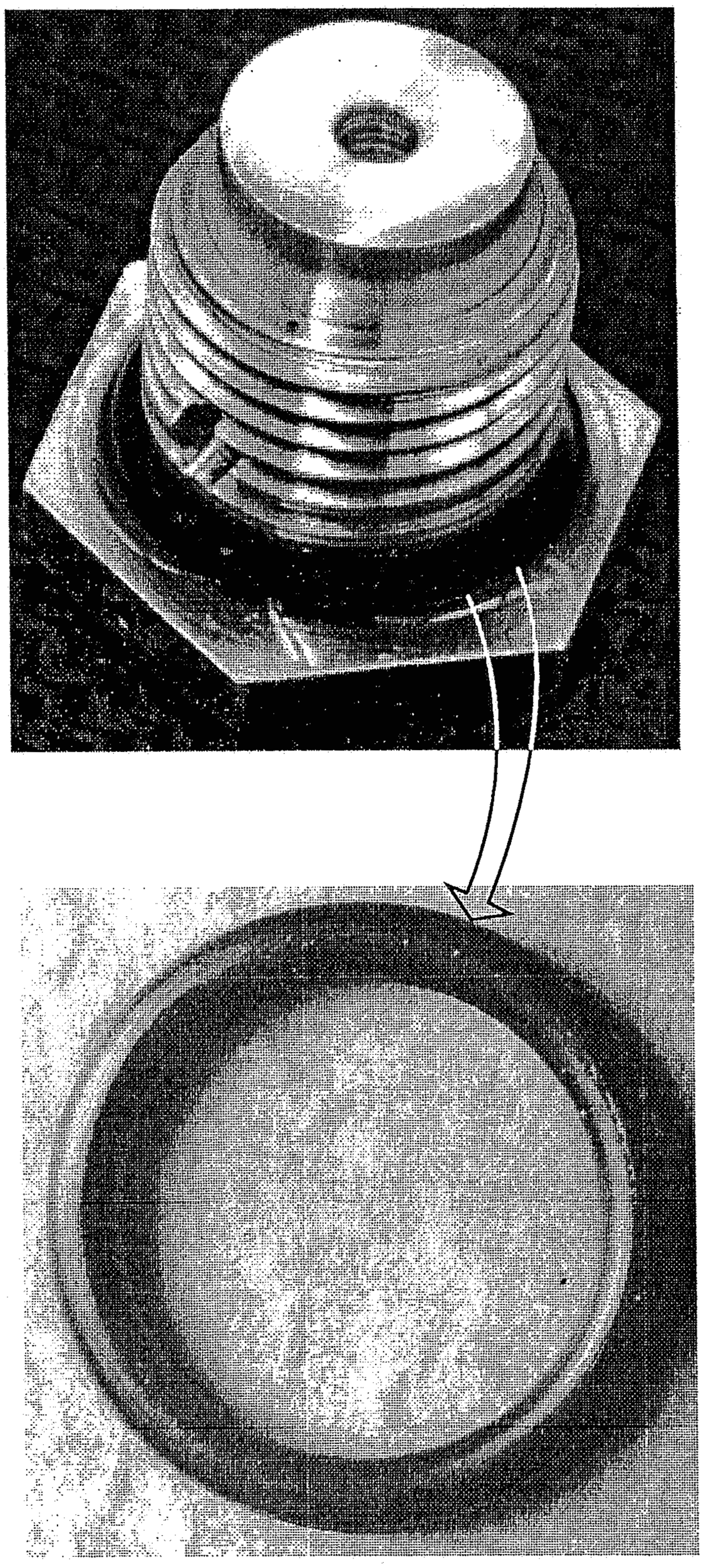


Figure 4-4. Viscous Damper Fill Port Plug Ethylene Propylene O-ring Seal.

Table 4-4 and figure 4-5 shows the results from mechanical testing of the control, nitrogen aged, and LDEF specimens. During testing the samples were strained at two inches per minute at 77°F. Both elastomers exhibited increases in maximum strength for the nitrogen and LDEF specimens. The LDEF NBR specimens exhibited a 55% increase in tensile modulus while similar specimens aged in nitrogen showed **a** slight decrease. Both EPDM LDEF and nitrogen aged specimens showed increases in tensile modulus (ref. 7).

SAMPLE	MODULUS (psi)	MAXIMUM STRAIN (%)	ULTIMATE STRESS (psi)
NBR Control	890	785	2430
NBR LDEF	1380	560	3530
NBR Nitrogen aged	840	585	2610
EPDM Control	600	500	2240
EPDM LDEF	780	710	2850
EPDM Nitrogen aged	880	735	2780

Table 4-4. Mechanical Property Data for EPDM and NBR Flown on P0005 (ref. 7).

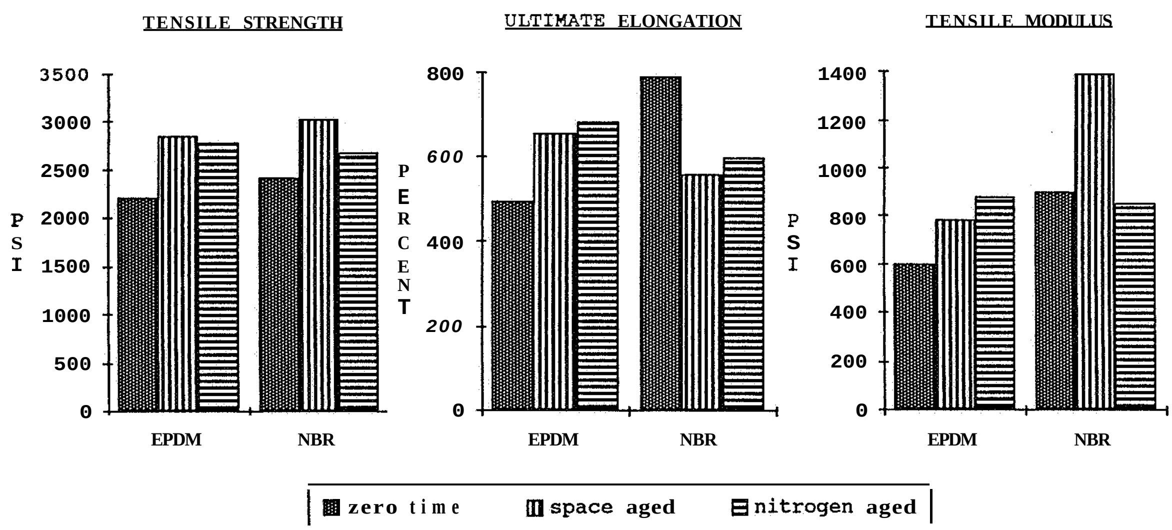


Figure 4-5. Performance of NBR and EPDM control, LDEF, and nitrogen aged specimens.

Silicone Rubber

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 (see figure 4-6). The hardness of the gasket was the same in exposed and unexposed areas, and all material was very pliable. Tensile strength and elongation were determined. Five specimens were tested and the average ultimate stress was 725 psi and the average elongation at failure was 100% (Appendix D-1 1 contains the test data sheet). Although control specimens were not available, the properties of the cushioning gasket were found to be within the range of other silicone elastomers.

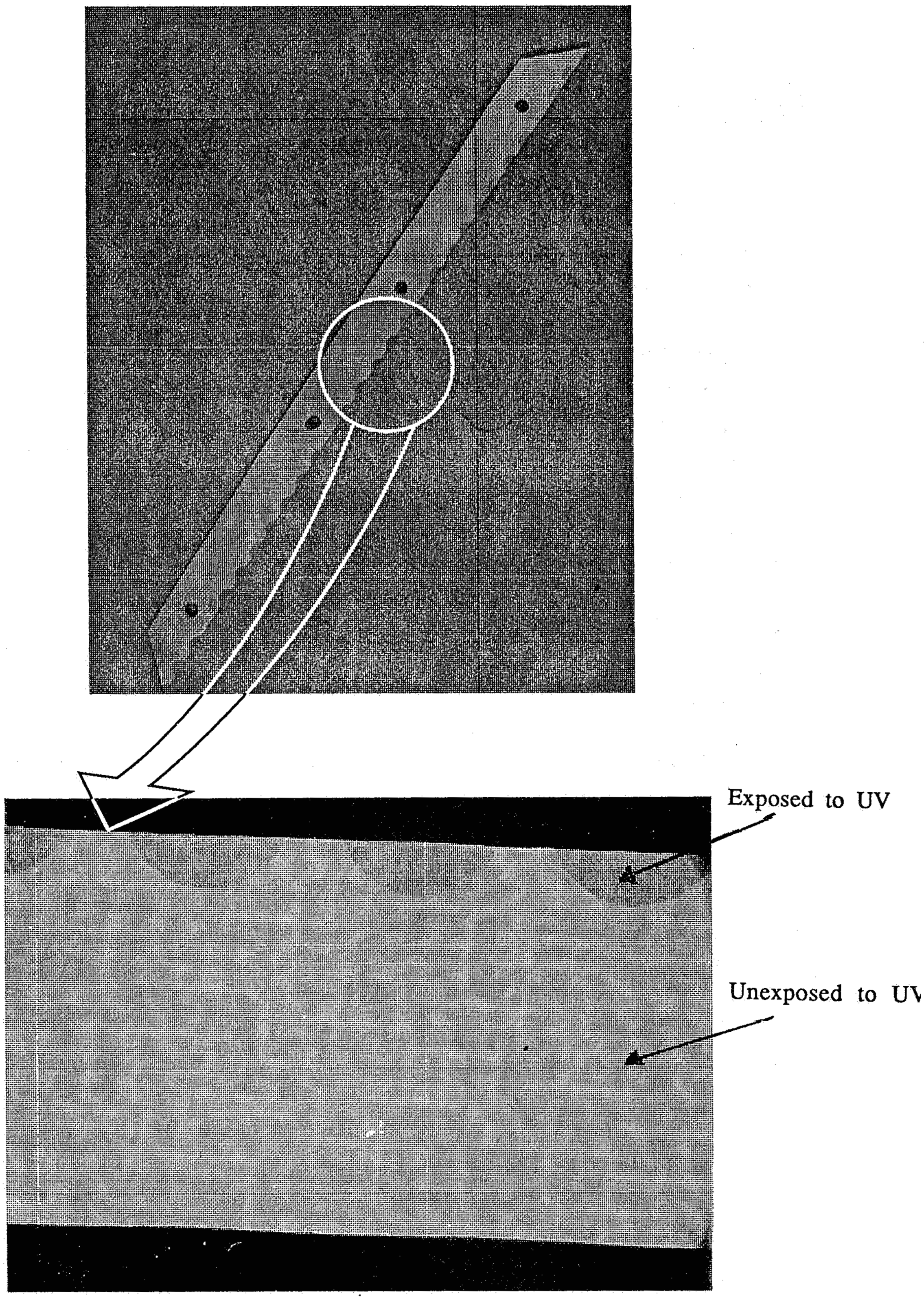


Figure 4-6. Silicon Rubber Cushioning Gasket Used on Experiment SO050.

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. Both the exposed and shielded rubber remained pliable and free of cracks. Some darkening of the rubber was observed in the exposed areas.

Viton

Table 4-5 shows the large number of Viton O-rings that were used on numerous LDEF experiments. Post flight examination showed that the ones examined were in nominal condition (O-rings that underwent known examination are underlined). No Viton O-ring seals failed to maintain a seal. None of the Viton O-rings were exposed to UV or to atomic oxygen.

Viton O-rings	
EXPERIMENT #	**SPECIFIC MATERIAL (if known)**
A0015	Viton B
<u>A0134/S0010</u>	MIL-R-83248
<u>A0138-2</u>	Skega Mfg
<u>A0138-2</u>	Vacour Mfg
A0139A	AMS 7280
<u>A0180</u>	
<u>A0189</u>	
<u>M0001</u>	Parker V747-15
M0002	C 76
<u>P0005</u>	
<u>S0069</u>	Used on the recorder
<u>MTMs</u>	

Table 4-5. Viton O-rings Used on LDEF.

A group of 28 Viton washers was used to pad the 14 quartz crystal oscillators in experiment A0189 located on tray D2. Figure 4-7 shows the position of the washers in the quartz crystal oscillators *(2* washers per oscillator). Post-flight durometer hardness measurements were performed on all 28 washers. The results were a range of 72 to 75 with a median value of 73 (Shore "A" gauge hardness). No control values were available. The washers were apparently sheared 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 faying (contacting) surfaces, indicating compression set. No further analysis was performed because the original compression was unknown.

Inconel 750 Metal Seal

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

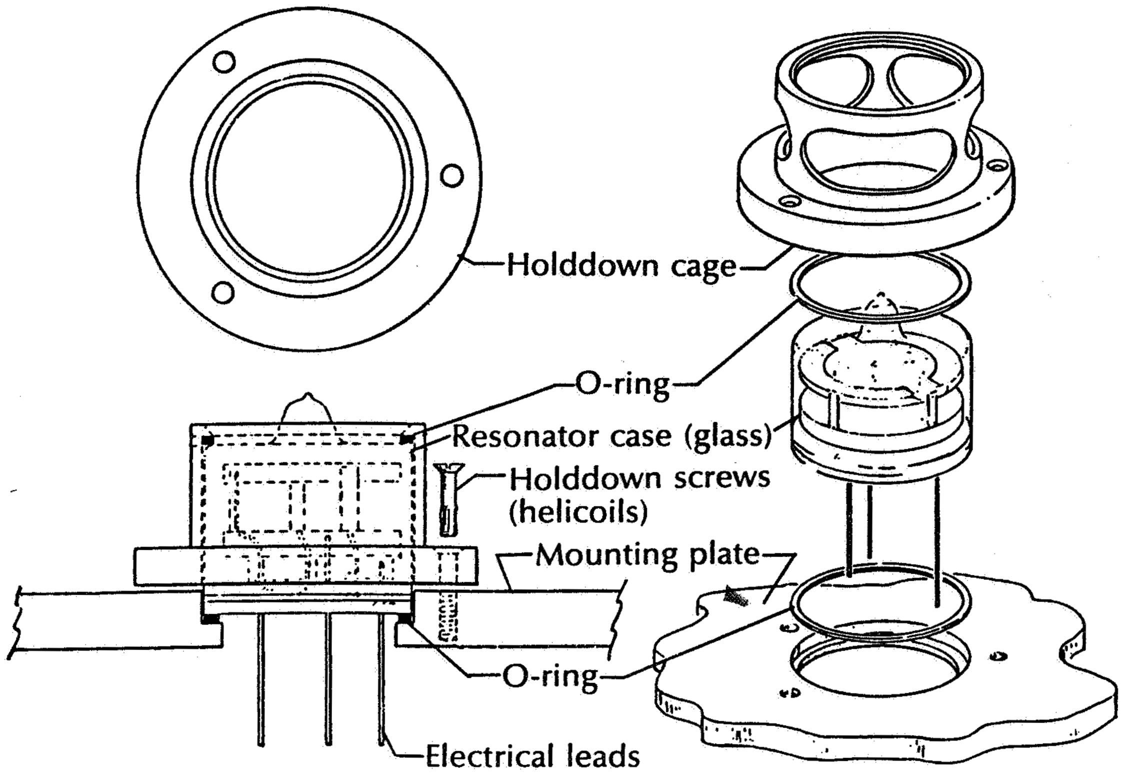


Figure 4.7. Location of Viton O-rings used on the Quartz Crystal Oscillators Flown on Experiment A0189

5.0 CONCLUSIONS

The vast majority of lubricants and seals flown on LDEF were shielded from direct or indirect exposure to the exterior spacecraft environment with the exception of the vacuum component of the LEO environment. Of the few specimens exposed to LDEFs exterior environments only the powdered MoS_2 used on the **A0138** canisters underwent any significant degradation. The results of this lubricant and seals investigation showed that if the material was shielded from direct or indirect exposure to atomic oxygen and/or UV, it was retrieved in nominal condition. The only on-orbit degradation of materials not exposed to the exterior spacecraft environment was outgassing or migration that was noted for two of the liquid lubricants. While this apparently had no effect on the lubricant's ability to function **as** designed, it did contribute to the overall molecular contamination that was found throughout LDEF.

Both the dry film lubricants used on LDEF and silver-plating proved to be an effective means of eliminating galling between the mating surfaces found within fastener assemblies. This ensured successful post-flight deintegration of LDEF hardware. However, future long-term flight experiments should include active experiments that evaluate the effects of long-term cycling of lubricants while on-orbit. LDEF results show that with the proper lubricants, no difficulties will be encountered during on-orbit or post-flight removal of fasteners. These results do not address the effects of the cycling of fasteners while on-orbit. The removal of fastener lubricants caused by on-orbit replacement of hardware could lead to severe galling or even coldwelding resulting in excessive installation/removal torques or fastener seizure.

If the lubricant or seal is required to be 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 to ensure that mission lifetime goals will be achieved.

6.0 REFERENCES

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2) Assie, J. P.; and Conde, E.: "Microwelding (or Coldwelding) of Various Metallic Materials Under the Ultra-Vacuum LDEF Experiment AO-138-10," *LDEF 69 Months in Space; First LDEF Post-Retrieval Conference,* NASA CP-3134, p. 1613, February 1992.

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4) Durin, C.: "Systems Related Testing and Analysis of FRECOPA," *W E F Materials **Workshop** '91,* NASA CP-316, November 1991.

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7) Lester, D. M.; Jones, L. L.; Smalley, R. B.; and Ord, R. N.: "Space Aging of Solid Rocket Materials," *LDEF 69 Months in Space; First LDEF Post-Retrieval Conference,* NASA CP-3134, p. 1225, February 1992

APPENDIX A
A0175 FASTENER REMOVAL TEST REPORT

Richard Vyhnal
Rockwell International
Tulsa, OK

FASTENER TORQUE MEASUREMENTS AND SEIZING PROBLEMS DURING TEARDOWN OF EXPERIMENT A0175 (TRAYS A1 & A7)

This report summarizes: (a) our experience with fastener seizing and (b) torque measurement data recorded during the removal of 7 graphite-reinforced composite panels from trays A1 and A7. [These two tray positions are diametrally opposed on LDEF, approximately 60-degrees respectively from the satellite's nominal trailing edge (Row 3) and leading edge (Row 9); here, the angle refers to that measured between normals to the tray surfaces.]

The fastener arrangement, shown in Figure 1, consists Of:

- o NAS1003-5A fasteners: A286 CRES
- o BACN10JN3CM nutplates: A286 CRES passivated, with cetyl alcohol lubricant (*),
- o AN960-C10L washers.

We attempted to follow the torque measurement guidelines provided by the LDEF Systems SIG (Special Investigation Group), but deviated from this procedure as the seizing problem became apparent (in an effort to understand its cause). This procedure involved use of a dial-gage torque wrench to:

(a) gradually apply a tightening torque equal to the original pre-flight installation torque, noting the angular rotation of the fastener, if any, and subsequently

(b) measure the breaking and running torque values during removal of the fastener.

Since torque readings had not been recorded during installation, we determined the allowable range of installation torque (23 - 30 in.lbs) per the applicable spec (ST0101LA0002) and selected a value midway in this range (26 in.lbs) as our maximum tightening torque.

If the fastener rotated during application of this torque, we recorded the torque value at which rotation started (see column A in Table I), continued until the 26 in.lb. value was reached, and then estimated the rotation angle (column B) by comparing the final head orientation with a record of the original orientation. Likewise during removal of the fasteners, we noted the torque value at which rotation started (column C - breaking torque) and the running value (column D). In the case of seizing, the maximum running value was recorded.

Table I summarizes the measurements taken; Figure 2 shows the numbering sequence for identifying each fastener.

In some cases, we were able to slide a panel out after loosening only three of the four retainer strips around its periphery, thus leaving a row of fasteners otherwise undisturbed for possible evaluation by the Systems SIG, if elected. It is expected that many of these fasteners will also exhibit seizing, galling, and stripping upon

....

(*) Note: The original molybdenum disulfide (MoS_2) dry film lubricant on these nutplates had been removed and replaced with cetyl alcohol, as will be discussed in more detail elsewhere in this report.

removal. In addition, all of the fasteners along the lower level of the trays (see A In Figure 1) have been ieft undisturbed and are likewise available for evaluation.

Briefly summarizing the results in Table I, of the 132 fasteners through the retainer strips around the panels in both trays, 102 were removed; of these, 38 exhibited a running-torque vatue significantly higher than the breaking torque, as manifested by selzlng, galling, thread stripping, and/or fracture of the fasteners in the threads.

In attempting to explain this phenomenon, two unrelated but potentially relevant pieces of information are included here.

First, in a documented discussion with NASA-Langley/LDEF personnel in 1979, concern was expressed about the use of MoS_2 dry film lubricant on the nutplates because of its possible volatilization while in orbit and contamination of the experiments. In response to this concern, the decision was made to remove this lubricant from the nutplates and to replace it with cetyl alcohol. While no specific records of this processing we're kept, according to current thinking, it would probably have involved a soak in a hot nitric acid solution to remove the MoS_2 followed by rinsing, drying, and soaking In a cetyl alcohol solution (perhaps as controlled by MIL-L-87132 "Lubricant, Cetyl Alcohol, 1-Hexadecanol, Application to Fasteners").

Second, seizing problems have been recently encountered with this same fastener material (A286 CRES bolt and nutplate) on another in-house program.

In this case, the fasteners were Alien-head bolts and the nutplates were beam-type locking nutplates. The latter are designed for repeated cycling (as opposed to the deformable-basket type which we used on LDEF). The threaded section of the nutplate contains two sllces'at 90-degrees to each other and parallel to the thread axis, creating 4 independent quarter-section threaded "beams". The fasteners were bare and the nutplates coated with MoS_2 dry film lubricant.

Our experience involved repeated insertion (by both hand and power-feed wrench) and removal (by hand only) of the fasteners to evaluate the "maintalnabllity" of this arrangement. Galling and thread wear were encountered, with a higher occurrence associated with power-Installed fasteners. Thread stripping was noted on bolts and nutplates, either singly or both, and some fastener heads were also stripped due to seizing in the threads. The problem was alleviated by the application of a heavy grease which enabled up to 50 cycles without damage.

Considering our difficulty in removing the LDEF fasteners together with the above pieces of Information, It Is speculated that A286 steel may be susceptible to "cold welding" to itself under conditions of "insufficient" lubrication, and that cetyl alcohol provides Insufficient lubrication to allow ease of disassembly under service conditions such as typified on the LDEF flight.

Finally, it is noted that the LDEF Materials SIG has previously expressed interest in performing chemical analysis on the cetyl alcohol lubricant. Based on our experience described herein, it may be appropriate to expand this evaluation of the fastener system. At this time, our trays have been shipped to NASA-JSC (Attn: Mike Zolensky) for re-examination of micrometeoroid impacts, afterwhich it is planned to forward them to Boeing (Attn: Gary Pippin) for further evaluation by the MSIG.

TABLE I

TRAY A1 Fastener No.	(A) Tightening Torque (in.lbs)	(B) Rotation Angle (degrees)	(C) Breaking Torque (in.lbs)	(D) Running Torque (in.lbs)	Comments
1	22	35	19	100	broke @ #7 thread (from head end)
2	26	0	24	65	stripped @ #9-13
3	26	0	22	100	"
4	26	0	23	95	
5	24	5	19	78	broke @ #7
6	26	0	27	80	stripped
7	26	0	28	85	"
8	26	0	29	82	
9	13	30	4	2	removed ok
10	26	0	28	110	broke @ #7
11	26	0	24	86	stripped
12	25	< 5	22	60	
13	(not measured)		42	2	removed ok
14			30	2	
15			24	2	
16			22	95	stripped
17-27 (20 21 22 23 24 25 26 27)	(left undisturbed for future evaluation)				
28			36	2	removed ok
29			20	30	
30			36	25	"
31	"	"	20	20	"
32	"	"	22	5	"
33	"	"	22	5	"
34	"	"	20	25	"
35-37	(after removing #31-34 & 38-41, cut #35-37 fastener heads off -- first applying any torque -- to allow removal of laminate and examination of these nutplates in the as-installed condition >> they all appeared undamaged)				
38	(not measured)		30	95	stripped
39			32	92	
40			32	80	
41			29	55	
42-44	(left undisturbed for future evaluation)				
45	(not measured)		40	8	
46			28	20	
47			38	70	
48			36	5	
49			28	10	
50			28	8	
51			25	10	
52			48	90	
53			80	10	
54			60	2	
55			22	30	
56			30	8	
58			50	20	
			90	20	

Circled fastener numbers identify fasteners that did <u>not</u> have their MoS_2 removed,

TABLE I (continued)

TRAY A1

Fastener No.	(A) Tightening Torque (in. lbs)	(B) Rotation Angle (degrees)	(C) Breaking Torque (in.lbs)	(D) Running Torque (in.lbs)	Comments
59	(not measured)		35	5	
60			34	10	
61			33	10	
62			33	10	
63			23	90	
64			24	64	
65	(fastener was potted in place -- left undisturbed)				
66	(not measured)		30	72	
67			32	93	
68			20	80	
69			10	78	
70			34	90	
71			42	95	
72			36	118	

TRAY A7

Fastener No.	Tightening Torque (in. lbs)	Rotation Angle (degrees)	Breaking Torque (in.lbs)	Running Torque (in.lbs)	Comments
73	(not measured)		20	85	badly stripped
74			12	1	removed ok
75			28	1	
76			36	112	badly stripped
77-82	(removed panel without loosening fasteners #77-82; expect seizing may occur in some of these upon removal)				
83	(not measured)		15	1	removed ok
84	14	25	20	1	
85	10	60	20	1	
86	12	10	22	1	
87	(not measured)		22	50	badly stripped
88			24	5	removed ok
89			23	20	
90			22	1	
91			25	1	
92			22	1	
93	26	0	28	82	badly stripped
94	26	0	24	82	
95	26	0	24	108	broke in #3 thread
96	26	0	30	1	removed ok
97	26	0	24	20	
98	24	20	24	1	
99	26	0	28	90	badly stripped

Tray **A7 was <u>not</u> examined.**

TABLE I (continued)

TRAY A7

Fastener No.	Tightening Torque (In.lbs)	Rotation Angle (degrees)	Breaking Torque (In.lbs)	Running Torque (In.lbs)	Comments
100	26	0	34	1	removed ok
101	26	0	30	1	"
102	26	0	26	1	
103	26	0	22	2	" "
104	26	0	29	1	"
105	26	0	28	1	
106	26	0	24	1	
107	26	0	25	1	
108	26	0	29	10	
109	26	0	42	30	"
110	26	0	23	15	
111	12	< 5	22	1	
112	26	0	23	1	
113	26	0	32	94	badly stripped
114	24	5	26	1	removed ok
115	26	0	26	1	
116	18	5	17	104	badly stripped
117	26	0	24	66	
118		0	22	20	removed ok
119		0	25	1	
120		0	30	1	"
121		0	26	1	"
122	22	< 5	25	1	
123	26	0	32	1	
124		0	28	1	
125		0	36	70	badly stripped
126		0	28	1	removed ok
127-132	(removed panel without loosening fasteners -- expect seizing to occur in some of these upon removal)				

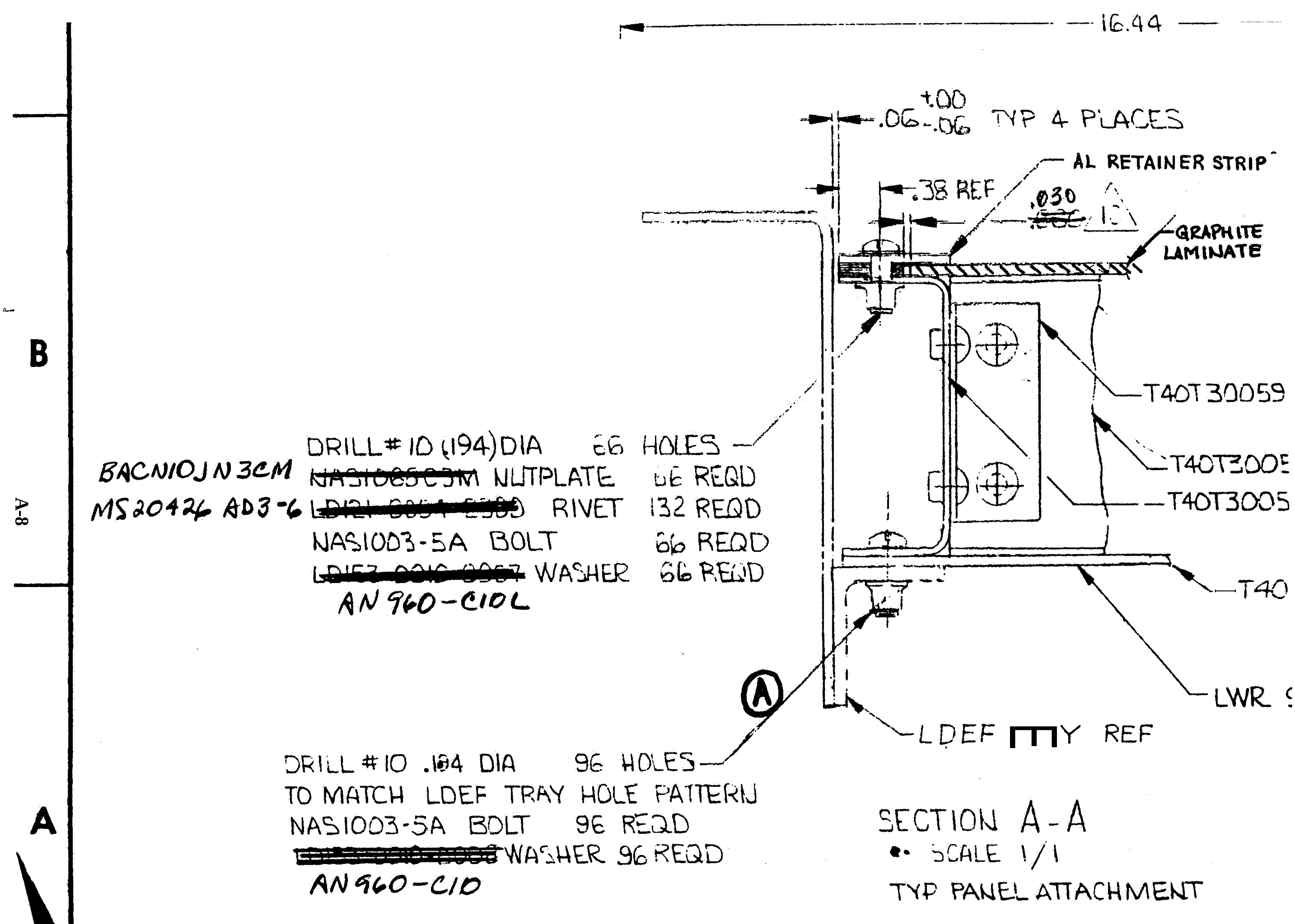
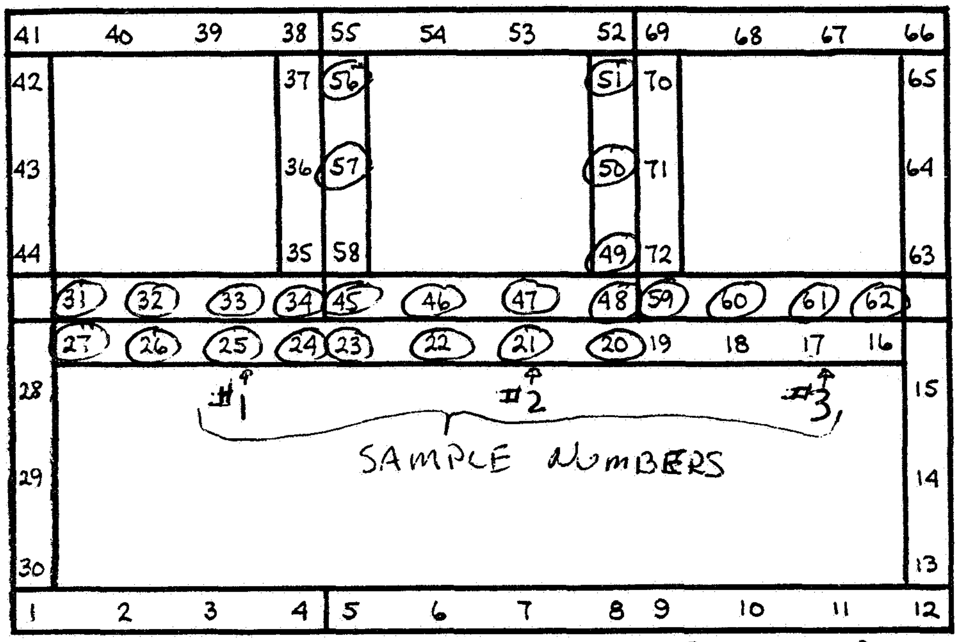


FIGURE 1. FASTENER COMPONENTS/ARRANGEMENT

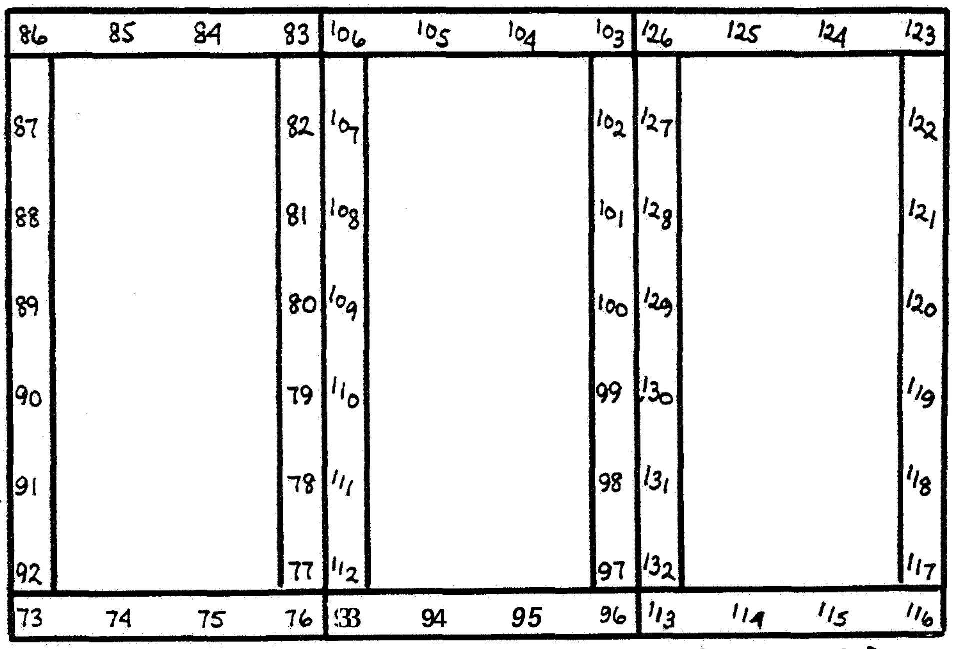
CIRCLED → VISUALLY HAVE MoS_2



(tray S/N)

A-1

TRAY A7 WAS NOT EXAMINED BY SYSTEMS SIG PERSONNEL



(tray S/N)

A-7

FIGURE 2. FASTENER IDENTIFICATION

APPENDIX B
BELLEVILLE WASHER TEST REPORT

Charles Domby
Boeing Defense & Space Group
Seattle, WA

ANALYTICAL ENGINEERING REPORT

TO: B. K. Keough 3H-30

cc:

REPORT NO.: 2-3623-WP-91-455

DATE: 11-13-91

MODEL: LDEF

LAB NO.: 1421

GROUP INDEX: **2-5323** Analytical Engineering - Metallurgical Analysis

SUBJECT: LDEF Belleville Washers

Sixteen belleville washers along with a spacer were submitted for evaluation. The washers had been stacked in series with the spacer at their ID. All parts had been coated with Mil-L-23389 dry lubricant. Visual inspection of the surface to determine if the LDEF mission had affected the lubricant was requested.

RESULTS AND DISCUSSION

Visual inspection at up to 30X was performed on the parts. The spacer appeared to be totally unaffected except for a slight burnishing of the surface where the washers had interfaced.

The washers had several interesting features. As shown in figure 1, some of the washers concave surfaces appeared to have a buildup of lubricant at the perimeter. These surfaces are where adjacent washers interface at their perimeter. Next to this buildup there was often an area devoid of lubricant, figure 1, area marked "A". This condition may be a space effect but it is postulated that this condition was caused by assembling the washers while they were still wet. It is possible that the solids in the lubricant were transported by a surface tension driven motion of the solvent (Marangoni Effect) prior to curing.

Burnished areas, seen as shiny area in figure 2, existed where adjacent washers interfaced. No abnormal wear was seen. Areas where the dry lubricant had thinned, often to bare metal, were present on some of the convex surfaces. As shown in figure 2, these surfaces had a similar appearance to the bare areas on the concave surfaces. It might be informative to see how these areas are oriented in the hardware. This information would be helpful in postulating whether the condition is a space effect or an original surface condition.

Prepared by: C.W. Domby
C. W. Domby
73-09, 237-7593

Approved by:
W. L. Plagemann
73-09, 234-3025

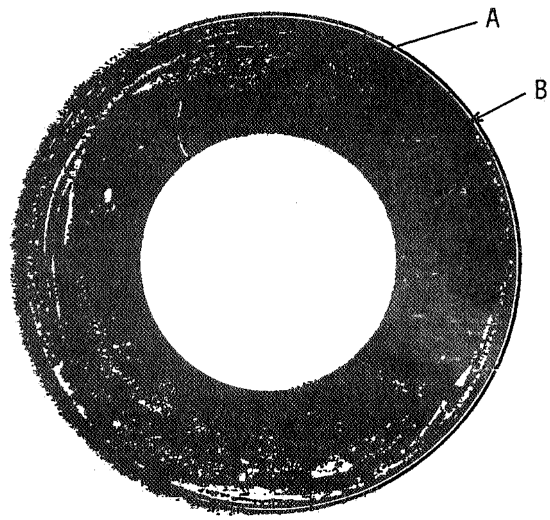


Figure 1: Concave surface of washer, showing area with no lubricant (A) and (B) lubricant buildup (3.2X).

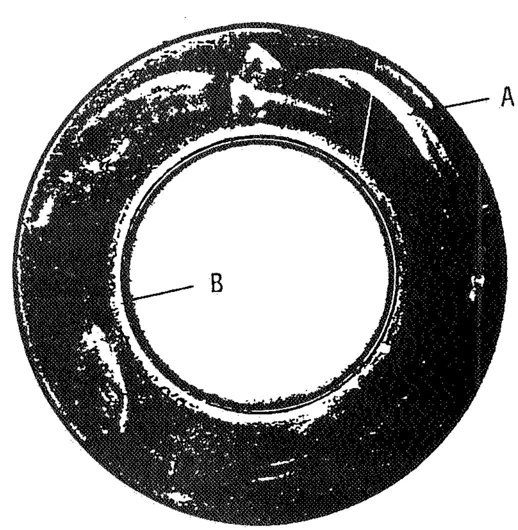


Figure 2: Convex surface of washer, showing area with no lubricant (A) and (B) burnished lubricant (3.2X).

APPENDIX C
EVALUATION OF ROD END BEARINGS FLOWN ON LDEF

New Hampshire Ball Bearings Inc.
Astro Division
Laconia, NH

New Hampshire Ball Bearings. Inc

NMB USA INC

REPORT NO. 191

AN EVALUATION OF ROD END BEARING, ASTRO P/N ADNE4J FLOWN ON THE LONG DURATION EXPOSURE FACILITY (LDEF)

BEARINGS MANUFACTURED BY:

NEW HAMPSHIRE BALL BEARINGS, INC.
ASTRO DIVISION
LACONIA, NEW HAMPSHIRE

TEST BY: Greg Ehlers DATE: 5 APRIL 1991

APPROVED BY: William A. Kuhn DATE: 5 APRIL 1991

New Hampshire Ball Bearings Inc

NMB USA INC

CERTIFICATE OF CONFORMANCE

The undersigned certifies that the data herein presented was generated by testing bearings manufactured by New Hampshire Ball Bearings, Inc. at their Astro Division facility located in Laconia, New Hampshire. The testing was performed at the NMB USA testing laboratory in Chatsworth, California. Testing was performed to compare the performance of bearings that had been exposed to a low Earth orbit for over 70 months with bearings that had not been so exposed. All work was performed by him or under his direct supervision. All information and dataherein presented is, to the best of his knowledge and belief, correct.

William A. Kuhn

William A. Kuhn
Engineering
Chatsworth, California
United States of America

New Hampshire Ball Bearings Inc

NMB USA INC

Date: 4 April 1991

Report No. 191

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(cont.)

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1.0 REFERENCES

ABBREVIATED FORM-	FULL REFERENCE DESCRIPTION
MIL-B-81820	Military Specification, MIL-B-81820E, dated 21 July, 1986. Bearings, Plain, Self-Aligning, Self-Lubricating, Low Speed Oscillation.
MIL-B-81935A	Military Specification, MIL-B-81935A, dated 1 June, 1987. Bearings, Plain, Rod End, Self-Aligning, Self-Lubrication, General Specification for.
MIL-B-81935/1B	Military Specification Sheet, MIL-B-81395/1B, dated 24 June, 1983. Bearing, Plain, Rod End, Self-Aligning, Self-Lubricating, Wide, Externally Threaded, -65°F to +325°F.
MIL-B-81935/1B-4	Bearing, Plain, Rod End, Self-Aligning, Self-Lubricating, Wide, Externally Threaded, -65°F to +325°F, .2500/.2495 Ball Bore.
MS14103-4	Bearing, Plain, Self-Lubricating, Self-Aligning, Low Speed, Wide, Grooved Outer Ring, -65°F to +325°F.
ADNE4J	Bearing, Plain, Rod End, Qualified and Conforming to MIL-B-81935/1B-4.

REFERENCES (Continued)

ABBREVIATED FORM	FULL REFERENCE DESCRIPTION
ADW4V	Bearing, Plain, Spherical, Self-Lubricating, Qualified and Conforming to MS14103-4.
LDEF	Long Duration Exposure Facility.

2.0 Objectives

The objective of the tests herein documented and described is to evaluate the performance of a self-lubricating bearing after a 70 month exposure in a low earth orbit. Three specimens of Astro Part Number ADNE4J were flown in the Long Duration Exposure Facility (LDEF). They were mounted on a tray located on the trailing edge of LDEF. They were exposed to ultraviolet radiation but no atomic oxygen. The module containing the bearings was provided by the Boeing Company, Boeing Defense and Space Group-, Aerospace and Electronics Division, P. O. Box 3999, Seattle, Washington, 98124-2499.

Two of the three specimens flown on the LDEF were made available for evaluation. Evaluation was made by comparing the LDEF specimens with production bearings taken from current Astro stock. These comparisons included visual appearance change, oscillating load performance, no-load torque, liner peel strength, etc.

3.0 Conclusions

The bearings tested were two LDEF specimens, Astro P/N ADNE4J, conforming to MIL-B-81935/1-4. The comparison specimens were Astro P/N ADNE4LJ conforming to MIL-B-81935/1L and Astro P/N ADW4V conforming to MS14103-4. Astro P/N ADNE4LJ differs from the LDEF specimens in that it has a left hand thread instead of a right hand thread, as denoted by the letter L in the part number. Astro P/N ADW4V is the bearing element specified for the Astro MIL-B-81935/1-4 rod end bearing.

The LDEF rod end bearings showed no degradation of oscillating load performance, pre-load torque loss or loss of liner peel strength. The only obvious difference between the LDEF specimens and the comparison rod end was a major loss of the chromate treatment applied to the cadmium plating. Bearing temperature recorded during the flight ranged from +14°C(+57°F) to +32°C(+90°F). This range is well within the -65°F to +325°F specified for these bearings.

Based on the performance of the parts as tested and described herein, there was no identifiable degradation of performance after 70 months exposure in the LDEF.

4.0 Test Methods and Results

4.1 Examination of Product

Two rod end bearings, Astro ADNE4J were received for evaluation. The threaded shanks had been shortened considerably, apparently by the use of a hand hack saw. These were identified as a long shank (LS) item and a short shank (SS) item for differentiating between the two specimens. Photograph No. 1 on page29 shows the items along with off-the-shelf comparison bearings.

The ADNE4J rod end is a male rod end conforming to and qualified to MIL-B-81820. Specifically, the part is built to and conforms to M81935/1-4. The bearing cartridge used in the rod end eye is built to and conforms to MS14103-4.

A request was made to handle these parts with cotton gloves during evaluation and testing. This proved to be impractical due to the nature of the testing and handling required. Part verification was by part number electrochemically etched on the rod end head. See photographs 2 and 3 on Pages 30 and 31.

The rod end bodies were cadmium plated per QP-P-416, Class 2, Type 11. Class 2 plating, is specified as being .00030 inches thick. No measurement of plating thickness was made on the two specimens. The Type II portion of the plating specification requires a supplementary chromate treatment over the basic cadmium plating. This coating gives the part an irridescent bronze color. The effect on the LDEF specimens was striking. See Photograph 4 on Page 32. Note loss of the chromate coating. Photographs 2 and 3 show the head of the rod ends with their identification markings. Here, there was a minimal loss of the chromate coating. Since there is a definite difference in chromate loss, the question of why arises. Based on the information available, no valid conclusion could be reached.

Visual inspection under the microscope at 10X showed some slight indentations on the long shank specimen in the 2-10 o'clock position of the rod end eye. Small indentations were also noted on the inner edge of the bearing race groove. These were probably tool induced during either installation or removal from the LDEF.

4.2 Preload Torque.

These bearings are manufactured with a specified no-load rotational preload torque. Manual rotation of these bearings is rather difficult because of their size. In order to evaluate their torque condition, it was decided to simply measure their misalignment torques and compare them with new bearing specimens. The results were as follows:

LDEF Short shank specimen:
.48 lbsf x 2.2 inches = 1.06 lb-inches.
LDEF Long shank specimen:
.90 lbsf x 2.2 inches = 1.98 lb-inches.
New Stock Rod End, ADNE4LJ:
.88 lbsf x 2.2 inches = 1.94 lb-inches.
New Stock Spherical Bearing, ADW4V specimen:
.63 lbsf x 2.2 inches = 1.39 lb-inches.

These torque values compare quite well with each other. The rotational torque allowables are 0.5 lb-inches to 6 lb-inches. Misalignment torques average about 35% of the rotational torques in this type of bearing. From this we conclude that the LDEF rod ends experienced no loss of torque because of their time in the LDEF.

4.3 Oscillating Load Testing.

The LDEF samples submitted for evaluation utilize a spherical bearing cartridge conforming to and qualified to MIL-B-81820. This cartridge is built to its appropriate MS, MS14103-4, and is required to meet a certain oscillating load/wear requirement. Oscillating load testing is performed by applying a unidirectional load to the bearing, oscillating it at ±25° at a 20 cpm frequency for a total of 25,000 cycles, at which time the allowable wear shall not exceed .0039 inches.

Testing the LDEF parts posed a problem. Because the rod end shanks had been shortened, tension load testing was suspect. Also, the load required to test the bearing cartridge is 4,900 lbsf. The ultimate static load rating of the rod end is 4,860 lbsf. Therefore, it was decided to test the short shank specimen under a tension loading of 2,450 lbsf, i.e., one half the MS requirement for the bearing cartridge. Another reason for testing at one half load was that there was no assurance the part would take the full MS load. If the first test was run at one half MS load, and it was successful we would have at least learned the part could function at one half load after LDEF exposure. The short shank part, at one half MS load, wore .0022 inches, or about 56% of the wear allowable.

Since the short shank bearing did so well at half load, it was decided to load the same bearing in compression at full MS load, i.e., the rod end eye was not being loaded in tension. This approach loaded the bearing liner on its untested side. The bearing wore .0031 inches or about 80% of its wear allowable at 25,000 cycles, it met specification requirements.

The long shank LDEF bearing was slso loaded in compression to the full MS load requirement. It wore .0029 inches or about 78% of its wear allowable at 25,000 cycles. It met specification requirements. Photograph 5 on page 33 shows the oscillating load test machine used for these tests.

As a base line for comparison, two ADW4V spherical bearings from stock were tested at one half and full MS load. At half load, the first specimen tested wore .0007 inches in 25,000 cycles. The specimen tested at full MS load wore .0013 inches in 25,000 cycles.

The wear plot data and log sheets are on pages 15 through 26.

Photographs 6, 7 and 8 on pages 34-36 show liner wear debris associated with these oscillating load tests. It must be pointed out that these bearings were highly loaded, the projected area stress based on ball diameter and effective race width being on the order of 34,000 psi, with a peak stress level of about 47,000 psi. Testing at these stress levels is a quality control/ specification requirement only. In actual usage, they see loads of about 20% of these stress levels. For space usage, they should readily accept the fairly high, short duration loads encountered during launch. Once in orbit, they are essentially in a zero G environment and the loads they see would probably be quite low. Under these loading conditions, the generation of wear debris demonstrated during these tests would be minimal, if any.

4.4 Liner Peel Strength

Another area of performance investigated on the LDEF specimens was that of liner peel strength. The applicable military specification specifies a minimum peel strength of 2.0 pounds force per inch of liner width. Because of the nature of these liner systems and the resins used, measurement is a problem. Photographs 9 and 10 show the method used. To get a liner specimen, the eye of the long shank bearing rod and eye was sawn through in the 5-7 o'clock position and the bearing cartridge removed. The cartridge was then sawn through to remove the ball. A section of the outer race, with the liner intact was placed in the vise as shown in Photograph 10 and a clamp affixed to one end of the liner. A motor driven table moving at the specification prescribed rate then peels the liner, the peeling force being fed to a strip recorder. This procedure was followed also on a current production part. The **LDEF** specimen recorded an average peel strength of 3.79 lbsf/inch, the reference specimen recorded an average peel strength of 2.64 lbsf/inch, both meeting specification requirements. From these data we can state that **70** months of **LDEF** flight had no distinguishable effect on liner peel strength.

Photograph 11 on page 39 shows the reference peel strength specimen. Photograph 12 on page 40 shows the **LDEF** specimen. Both show the liner wear surface, the rear of the liner surface and the glue line retained on the race. The liner system consists of a porous teflon membrane imbedded in a Nomex open weave cloth using a phenol formaldehyde thermosetting resin. The resin is also used to bond the liner system to the inner surface of the bearing outer race.

4.5 Summary.

All of the performance tests conducted met or exceeded MS specification requirements. The only noticeable effect as the result of the flight was some loss of the chromate treatment applied to the cadmium plate.

5.0 Test Equipment and Fixture List

5.1 Test Equipment

a. Oscillating Load Cycling Machine, 3/4 HP, 20,000 lbsf load capacity, two station, TF-10023.
b. Indicator, Dial Mitutoyo Model 2805, 0.0001 inch graduations, 0.050 inch range.
c. Force Gage, Chatillon Model DFGR10, 0-10 lbsf range, 0.01 lbsf resolution, S/N 2342.
d. Stand, motorized, Chatillon Model LTCM-4, S/N 8901-20.
e. Recorder, Two Channel, Allen Datagraph Model 2125M, S/N 8738.

5.2 Fixturing, Oscillating Load

Holder, Spherical Bearing	TF-10031-2
Holder, Male Rod End Bearing	TF-10078-1
Shaft, Test	TF-10028-2
Bushing, Spindle Adapter	TF-10029-2

New Hampshire Ball Bearings. Inc

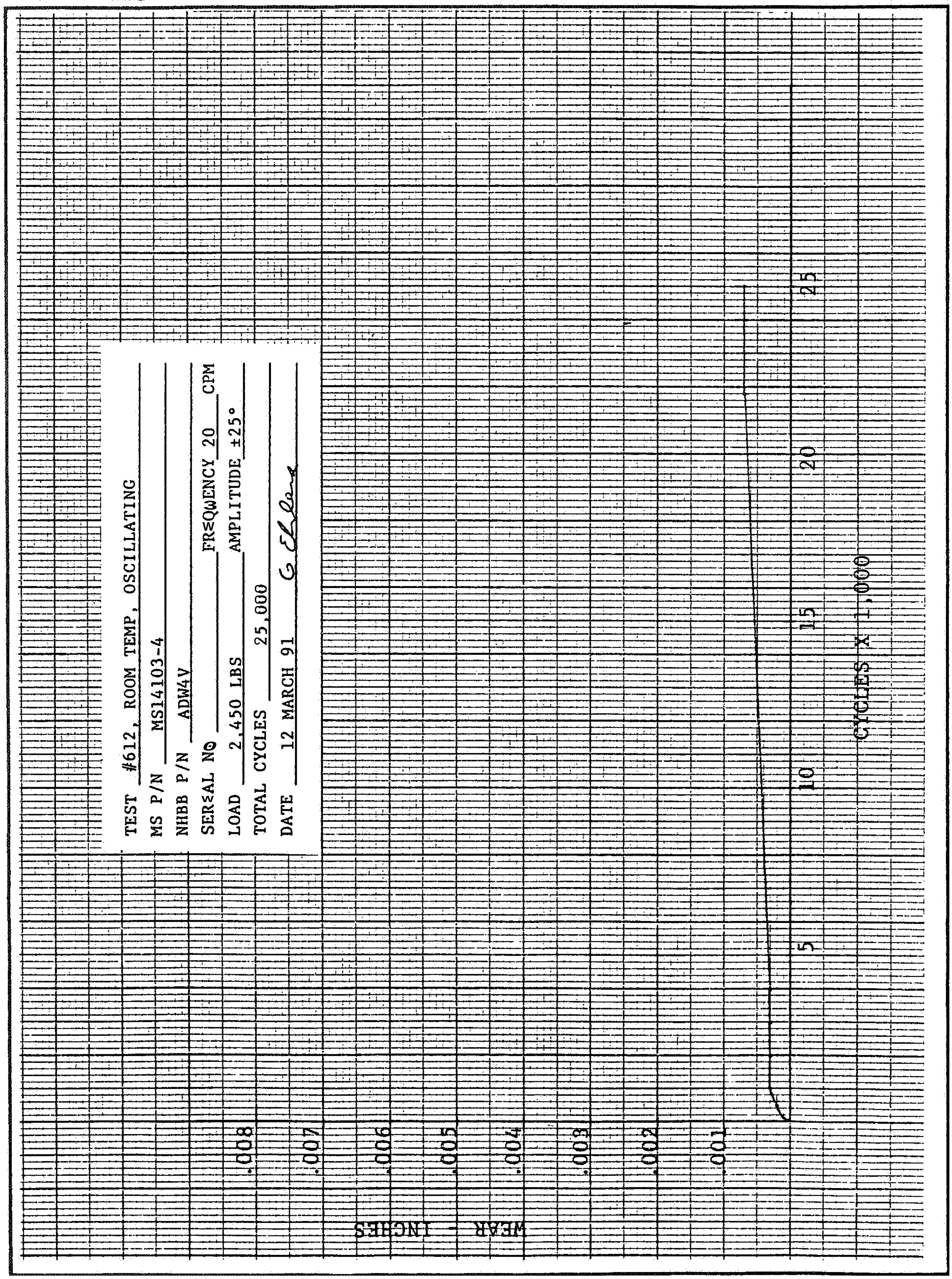
NMB USA INC

ADW4V, HALF
MS LOAD, BASE
LINE REFERENCE,
TEST #612

Date: 4 April 1991

Report No. 191

Page ~~15~~ of 40



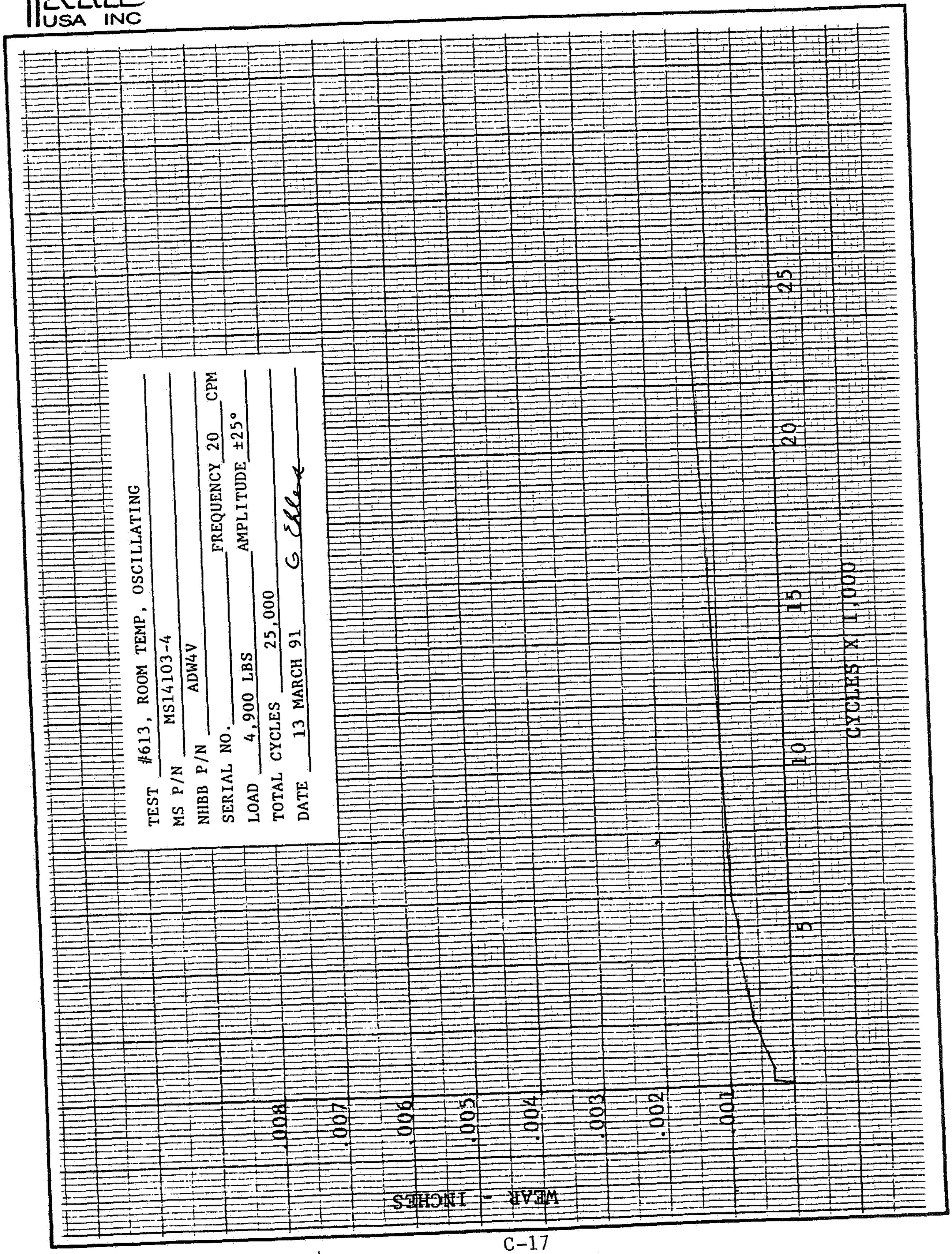
New Hampshire Ball Bearings, Inc.

NMB USA INC

ADW4F, FULL MS
LOAD, BASE LINE
REFERENCE, TEST #613

Date: 4 April 1991

Report No. 191



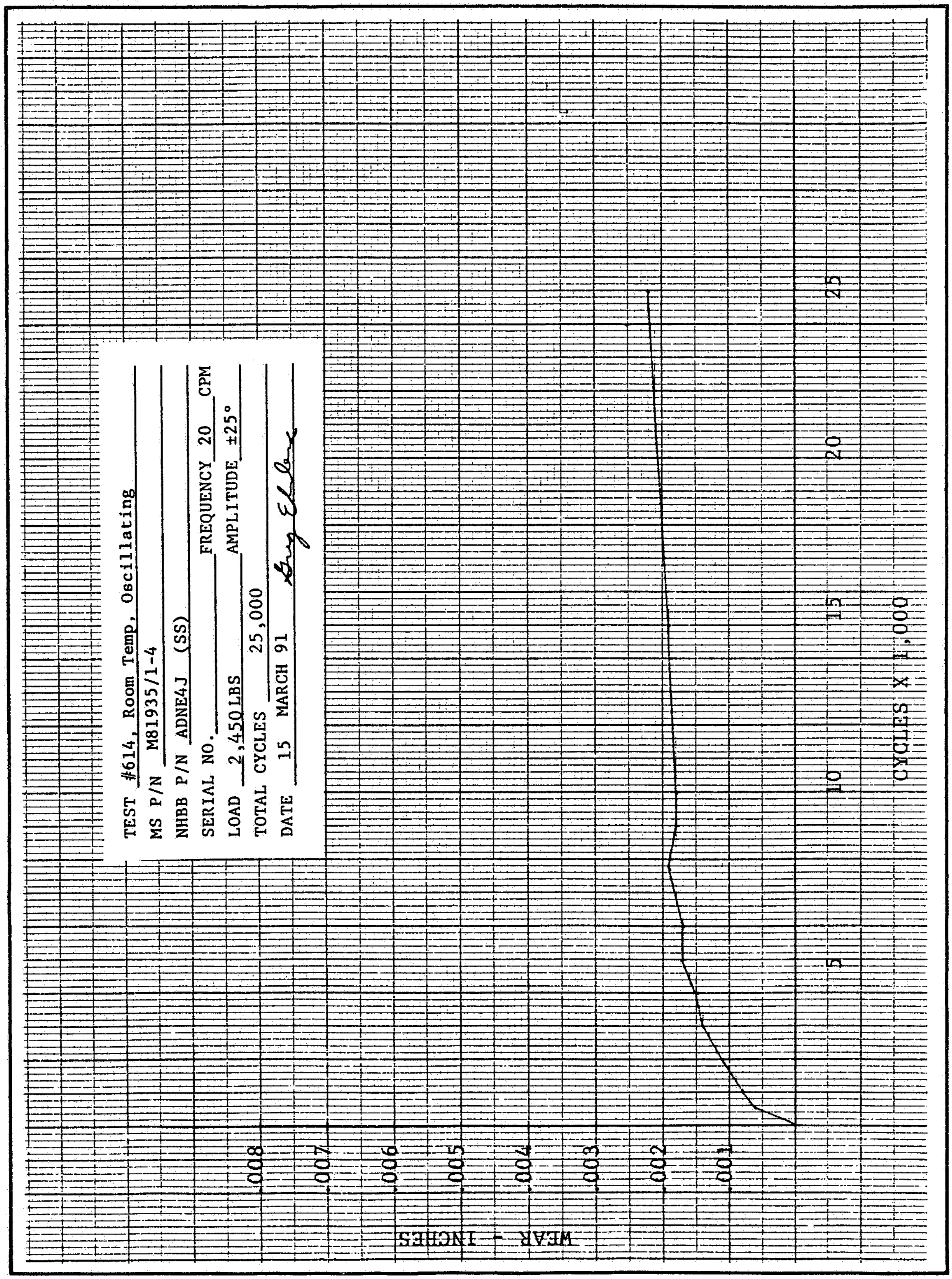
New Hampshire Ball Bearings Inc

NMB USA INC

ADNE4J (SS) ONE HALF MS LOAD, TENSION, TEST #614

Date: 4 April 1991

Report No. 191



New Hampshire Ball Bearings, Inc

NMB USA INC

ADNE4J (SS) FULL
MS LOAD, COMPRESSION,
TEST #615

Date: 4 April 1991

Report No. 191

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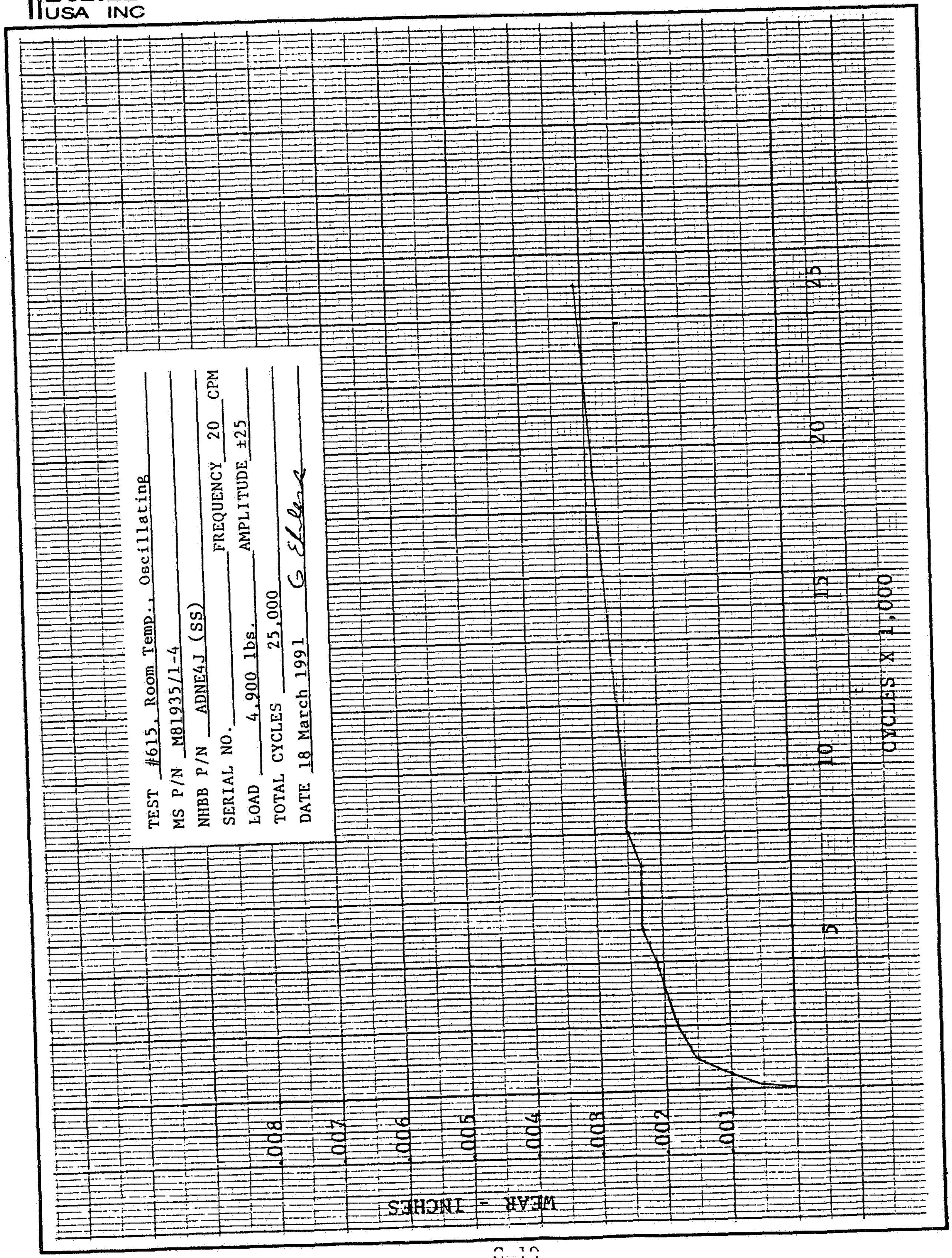
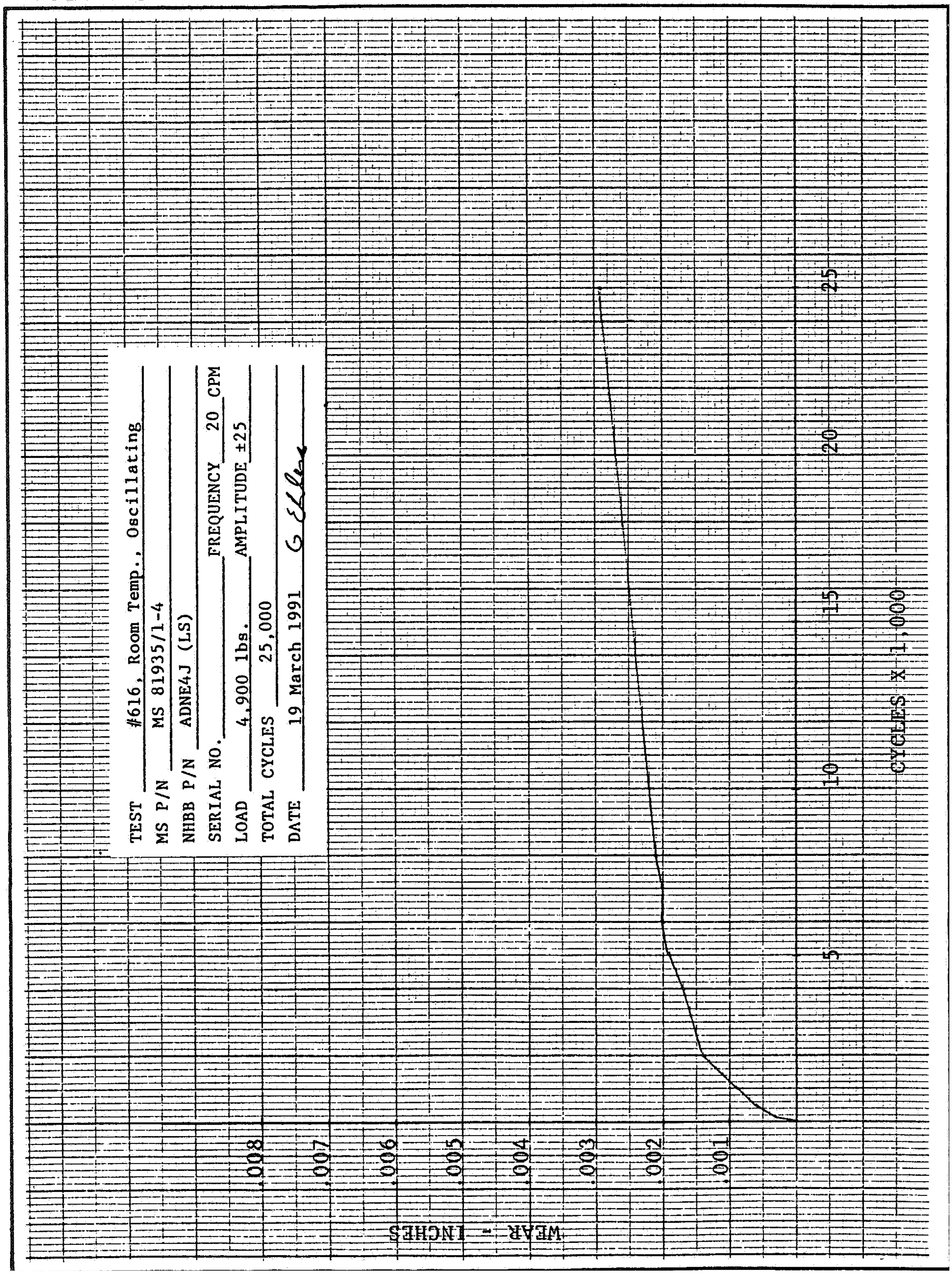



TEST #616, Room Temp., Oscillating
MS P/N MS 81935/1-4
NHBB P/N ADNE4J (LS)
SERIAL NO.
FREQUENCY 20 CPM
LOAD 4,900 lbs.
AMPLITUDE ±25
TOTAL CYCLES 25,000
DATE 19 March 1991
.008
.007
.006
.005
.004
.003
.002
.001
WEAR - INCHES
5
10
15
20
25
CYCLES X 1,000

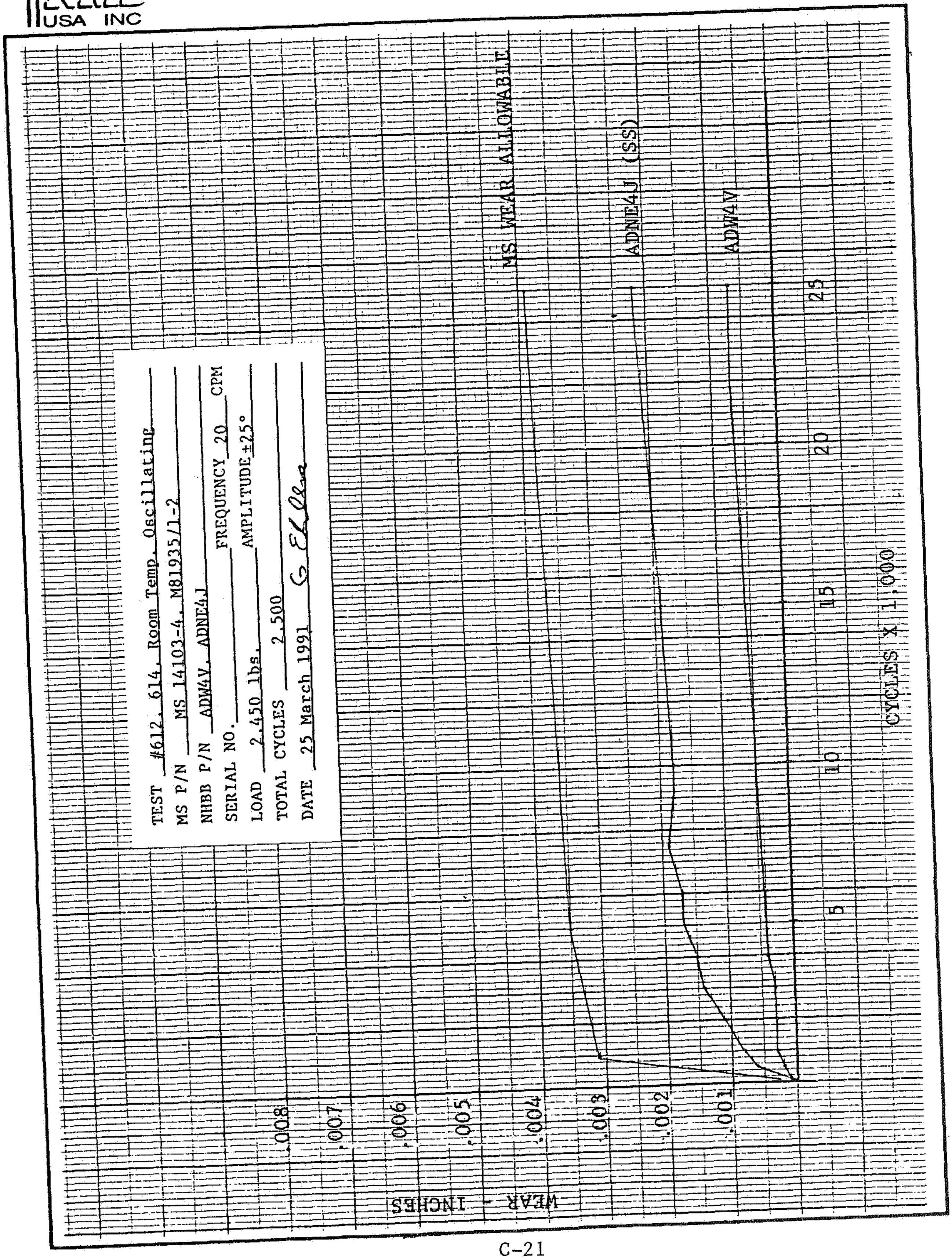
New Hampshire Ball Bearings, Inc

NMB USA INC

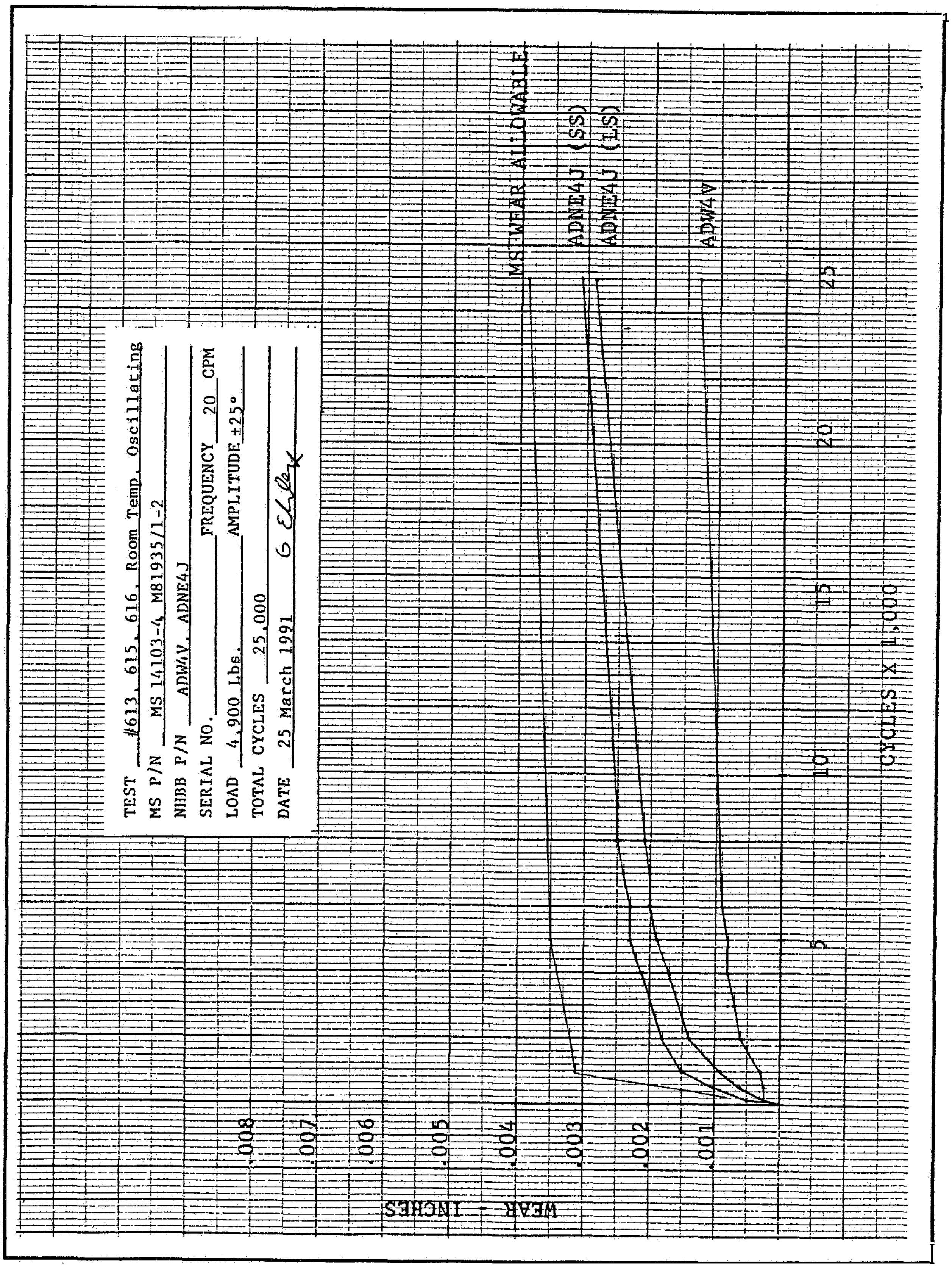
ADNE4J (SS) AND
ADW4V COMPARISON
ONE HALF MS LOAD,
ROOM TEMPERATURE

Date: 4 April 1991

Report No. 191



ADNE4J (LS) AND (SS) FULL MS LOAD COMPARISON WITH ADW4V ROOM TEMPERATURE



New Hampshire Ball Bearings Inc

NHBB USA INC

Date: 4 April 1991

Report No. 191

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LOG SHEET
WEAR TEST NO. 612
ADW4V, HALF MS LOAD

PART NO. ADW4V

TEST NO. 612

LINER TYPE L 1291

MAX. ALLOWABLE WEAR .0037 IN.

FREQUENCY, CPM 20

CYCLES REQUIRED 25000

AMPLITUDE ± 25 DEGREES

SHEET 1 OF

LOAD, POUNDS 2450 LBS

LOAD APPLIED AT 1:45 HRS.

PRESSURE, PSIG 295

MACHINE STARTED AT 2:00 HRS.

DATE: 11 MO: MAR YEAR: 91

TEST BY: Ehlers

SPECIAL KOTES/INSTRUCTIONS

Base Line Reference
For Long Term Exposure
To Space

READ MAX (+) ON DIAL INDICATOR
( ) TENSION (✓) COMPRESSION

LOAD = 1/2 MS LOAD

DATE	WEAR LEFT	TEMP LEFT	WEAR RIGHT	TEMP RIGHT	COUNTER CYCLES	TOTAL CYCLES
3/11/91			.0001		100	100
3/11/91			.0002		500	500
3/11/91			.0003		1000	1000
3/11/91			.0003		2000	2000
3/11/91			.0003		3000	3000
3/11/91			.0004		4000	4000
3/12/91			.0007		21800	21800
3/12/91			.0007		25000	25000

New Hampshire Ball Bearings, Inc

NHBB USA INC

LOG SHEET
WEAR TEST NO. 613
ADW4V, FULL MS LOAD

Date: 4 April 1991

Report No. 191

PART NO. ADW4V

TEST NO. 613

LINER TYPE L1291

FAX. ALLOWABLE WEAR .0037 IN.

FREQUENCY, CPM 20

CYCLES RZQUIRED 25000

AMPLITUDE ± 25 DEGREES

SHEET 1 OF 1

LOAD, POUNDS 4900

LOAD APPLIED AT 11:00 HRS.

PRESSURE, PSIG 719

MACHINE STARTED AT ______ HRS.

DATE: 12 MO: MAR YEAR: 91

TEST BY; EHLERS

SPECIAL NOTES/INSTRUCTIONS
BASE LINE REFERENCE
FOR LONG TERM EXPOSURE
TO SPACE

READ FAX (−) ON DIAL INDICATOR
(✓) TENSION ( ) COMPRESSION

FULL MS LOAD

DATE	WEAR LEFT	TEMP LEFT	WEAR RIGHT	TEMP RIGHT	COUNTER CYCLES	TOTAL CYCLES
3/12/91			.0003		100	100
3/12/91			.0003		500	500
3/12/91			.0004		1000	1000
3/12/91			.0006		2000	2000
3/12/91			.0007		3000	3000
3/12/91			.0008		4000	4000
3/12/91			.0008		5000	5000
3/12/91			.0009		6000	6000
3/13/91			.0013		25000	25000

New Hampshire Ball Bearings, Inc.

NHBB USA INC

New Hampshire Ball Bearings Inc

NMB USA INC

LOG SHEET
WEAR TEST NO. 614
ADNE4J (SS) HALF MS LOAD

Date: 4 April 1991

Report No. 191

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PART NO. NE4J (SS) TEST NO. 614

LINER TYPE L1291 MAX. ALLOWABLE WEAR .0037 IN.

FREQUENCY, CPM -- CYCLES REQUIRED 25000

AMPLITUDE ± 25 DEGREES SHEET 1 OF 1

LOAD, POUNDS 2450 LOAD APPLIED AT 10:00 HRS.

PRESSURE, PSIG 360 MACHINE STARTED AT 10:15 HRS.

DATE: 13 MO: MAR YEAR 91 TEST BY: EHLERS

SPECIAL NOTES/INSTRUCTIONS

LONG TERM EXPOSURE TO SPACE BEARING IN SPACE FOR 70 MONTHS

READ MAX (—) ON DIAL INDICATOR
(✓) TENSION ( ) COMPRESSION

1/2 MS LOAD FOR CARTRIDGE

12:00 SIDE TESTED

DATE	WEAR LEFT	TEMP LEFT	WEAR RIGHT	TEMP RIGHT	COUNTER CYCLES	TOTAL CYCLES
3/13/91			.0001		100	100
3/13/91			.0006		500	500
3/13/91			.0008		1000	1000
3/13/91			.0011		2000	2000
3/13/91			.0014		3000	3000
3/13/91			.0015		4000	4000
3/13/91			.0017		5000	5000
3/13/91			.0017		6000	6000
3/14/91			.0019		7722	7722
3/14/91			.0018		9000	9000
3/14/91			.0018		10000	10000
3/14/91			.0019		15000	15000
3/15/91			.0022		25000	25000

New Hampshire Ball Bearings Inc

NHBB USA INC

LOG SHEET

WEAR TEST NO. 615

ADNE4J (SS) FULL MS LOAD

Date : 4 April 1991

Report No.

PART NO. ADNE4J (SS)

TEST NO. 615

LINER TYPE L1271

MAX. ALLOWABLE WEAR .0037 IN.

FREQUENCY, CPM

CYCLES REQUIRED 25000

AMPLITUDE ± 25 DEGREES

SHEET 1 OF 1

LOAD, POUNDS 4900

LOAD APPLIED AT 9:15 HRS.

PRESSURE, PSIG 591

MACHINE STARTED AT 9:30 HRS.

DATE: 15 MO: MAR YEAR: 91

TEST BY: Ehlers

SPECIAL NOTES/INSTRUCTIONS

LONG TERM EXPOSURE TO SPACE

BEARING IN SPACE FOR 70 MONTHS

READ MAX (+) ON DIAL INDICATOR

( ) TENSION (✓) COMPRESSION

FULL MS LOAD FOR CARTRIDGE

6:00 SIDE TESTED

DATE	WEAR LEFT	TEMP LEFT	WEAR RIGHT	TEMP RIGHT	COUNTER CYCLES	TOTAL CYCLES
3/15/91			.0005		100	100
3/15/91			.0010		500	500
3/15/91			.0015		1000	1000
3/15/91			.0018		2000	2000
3/15/91			.0021		4000	4000
3/15/91			.0023		5000	5000
3/15/91			.0023		6000	6000
3/15/91			.0024		7000	7000
3/15/91			.0025		8000	8000
3/15/91			.0025		9000	9000
3/18/91			.0031		25000	25000

New Hampshire Ball Bearings. Inc

NHBB USA INC

New Hampshire Ball Bearings, Inc

NHBB USA INC

LOG SHEET
WEAR TEST NO. 616
ADNE4J (LS) FULL MS LOAD

Date: 4 April 1991
Report No. 191
Page ~~26~~ of 40

PART NO. ADNE 4J (LS)
TEST NO. 616

LINER TYPE L 1291
MAX. ALLOWABLE WEAR .0037 IN.

FREQUENCY, CPM 20
CYCLES REQUIRED 25000

AMPLITUDE ± 25 DEGREES
SHEET 1 OF

LOAD, POUNDS 4900
LOAD APPLIED AT 09:30 HRS.

PRESSURE, PSIG 591
MACHINE STARTED AT 09:45 HRS.

DATE: 18 MO: MAR YEAR: 91
TEST BY: Ehlers

SPECIAL NOTES/IESTRUCTIOES
LONG TERM EXPOSURE
TO SPACE
BEARING IN SPACE FOR
70 MONTHS

READ MAX (+) ON DIAL INDICATOR
( ) TEESION (✓) COMPRESSION

FULL MS LOAD FOR
CARTRIDGE
6:00 SIDE TESTED

DATE	WEAR LEFT	TEMP LEFT	WEAR RIGHT	TEMP RIGHT	COUNTER CYCLES	TOTAL CYCLES
3/18/91			.0003		100	100
3/18/91			.0006		500	500
3/18/91			.0009		1000	1000
3/18/91			.0014		2000	2000
3/18/91			.0017		4000	4000
3/18/91			.0019		5000	5000
3/18/91			.0020		6000	6000
3/18/91			.0020		7000	7000
3/18/91			.0021		8000	8000
3/19/91			.0029		25000	25000

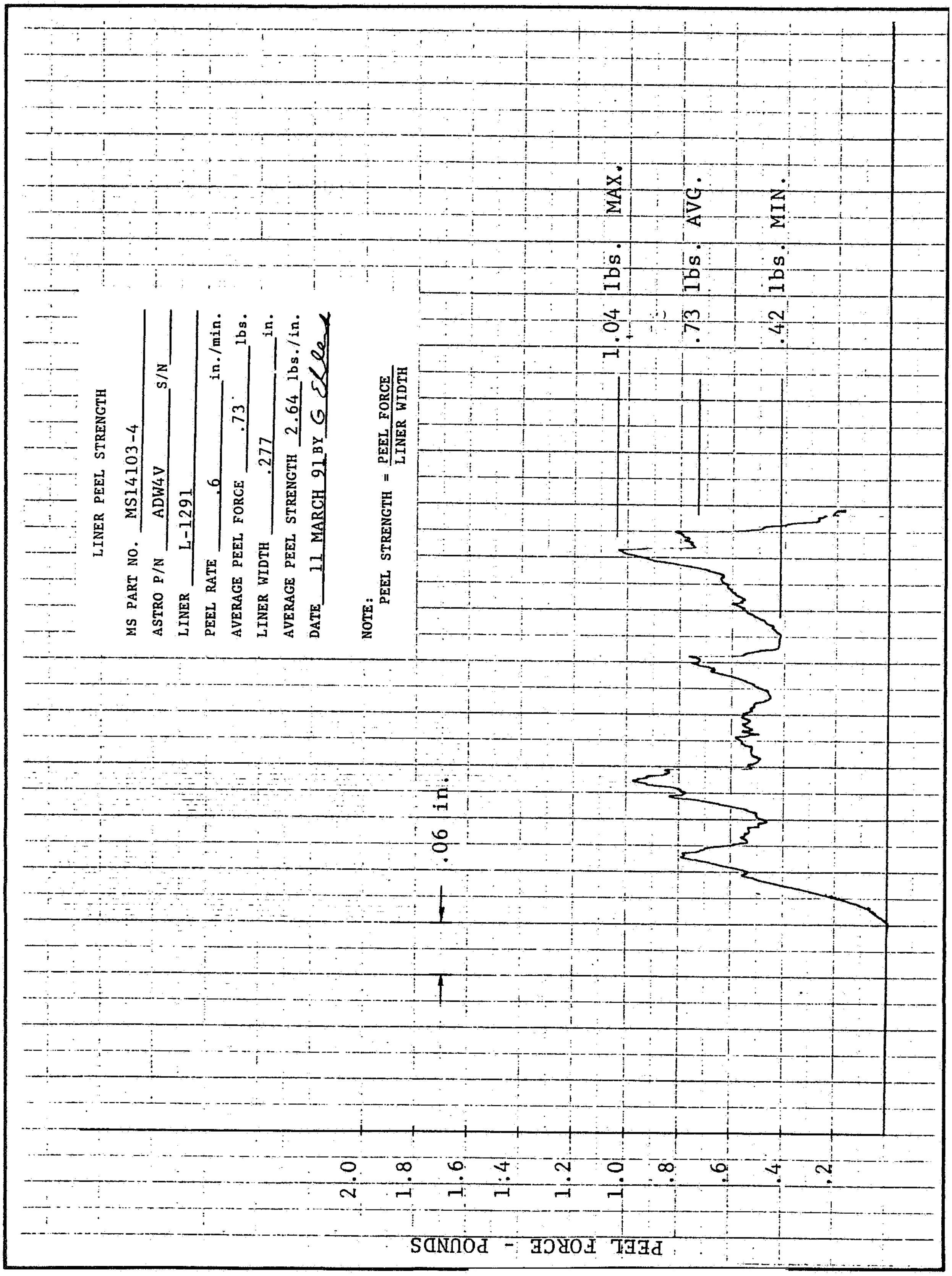
New Hampshire Ball Bearings Inc

NHBB USA INC

LINER PEEL STRENGTH TEST, ADW4V (REFERENCE)

Date: 4 April 1991

Report No. 191

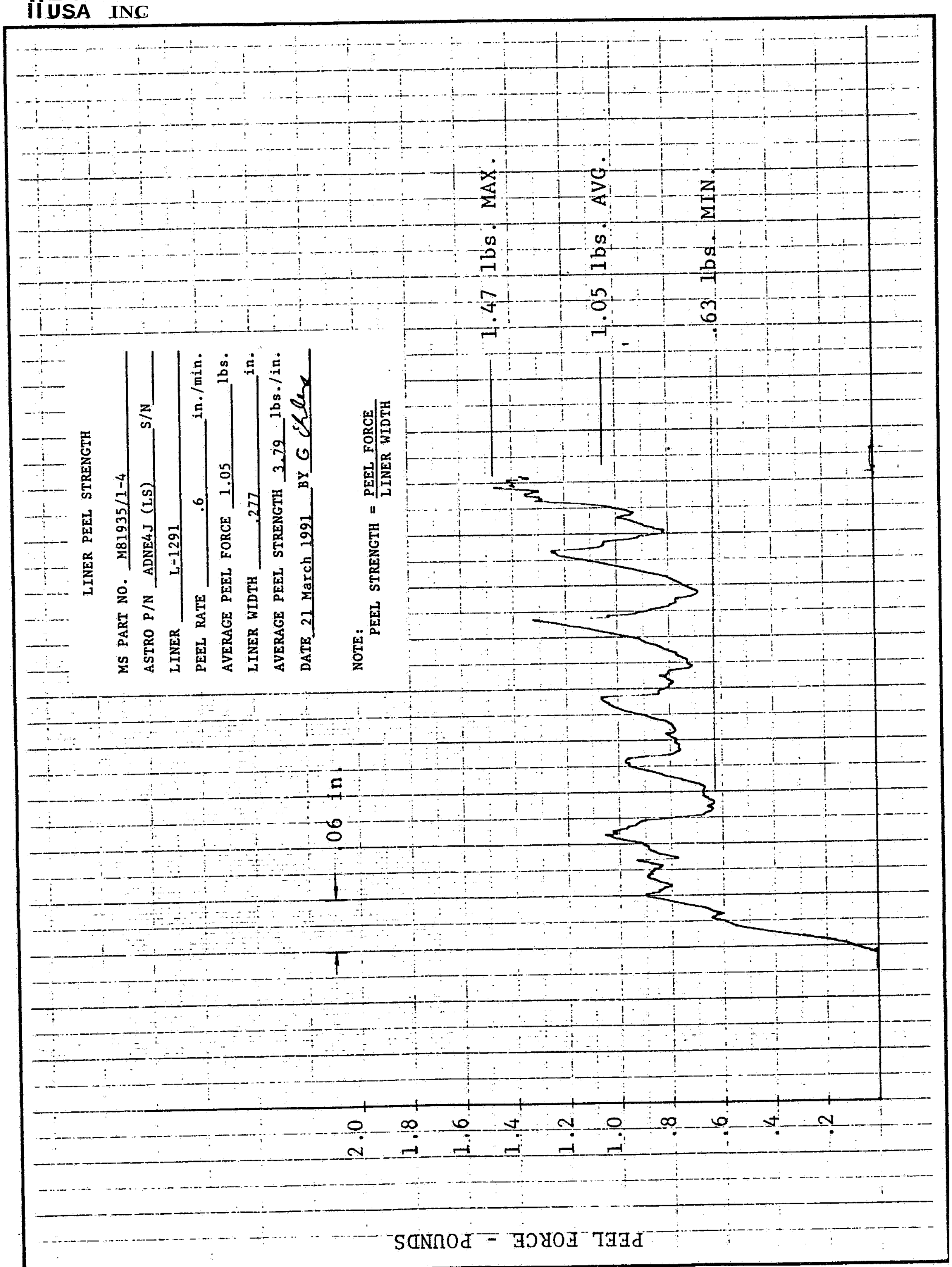


New Hampshire Ball Bearings Inc
NMB USA INC

LINER PEEL STRENGTH TEST, ADNE4J (LS)

Date: 4 April 1991

Report No. 191

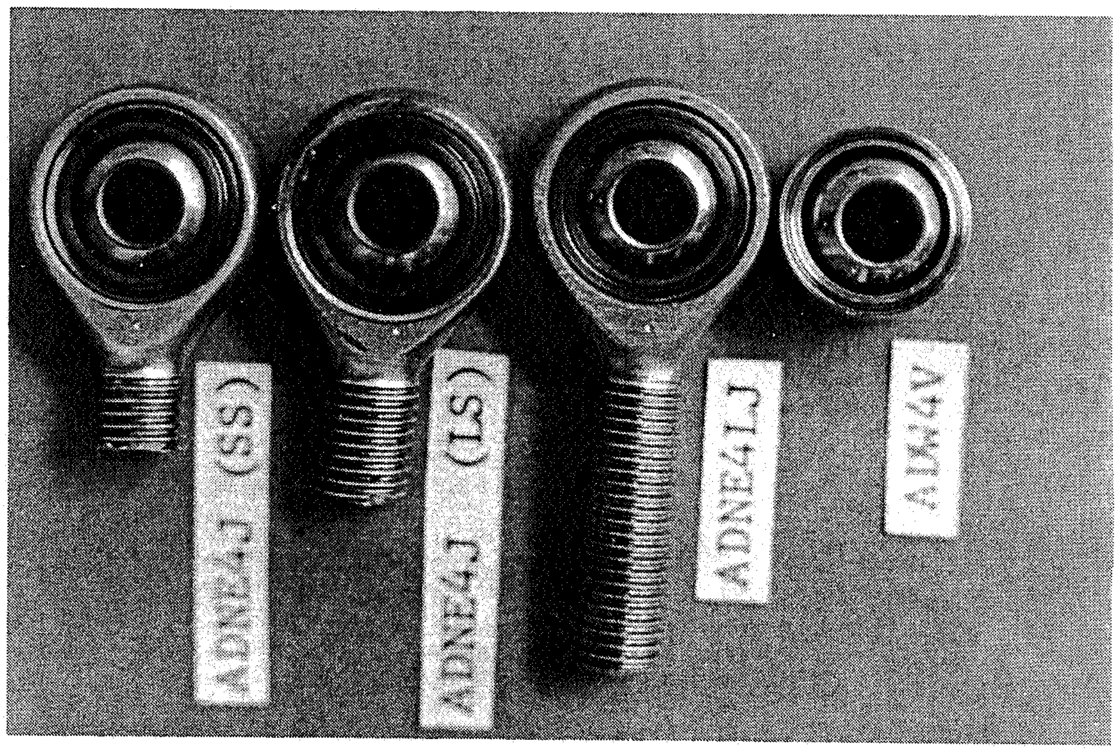


New Hampshire Ball Bearings, Inc

NMB USA INC

Date: 4 April 1991

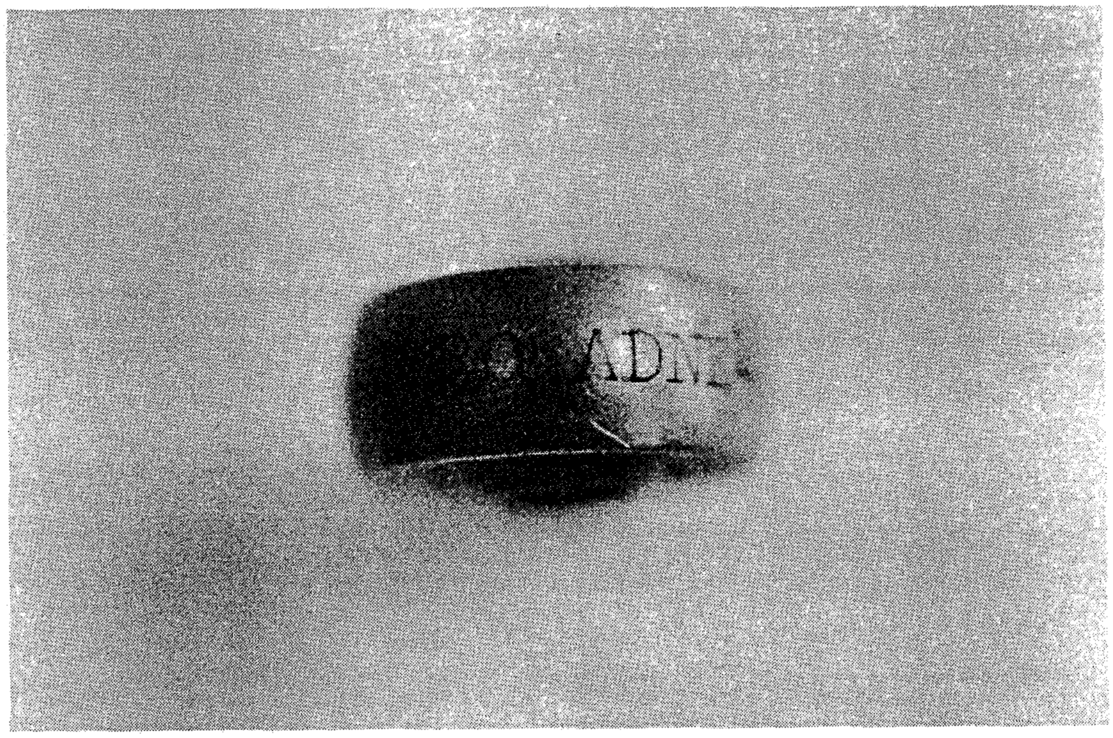
Report No. 191



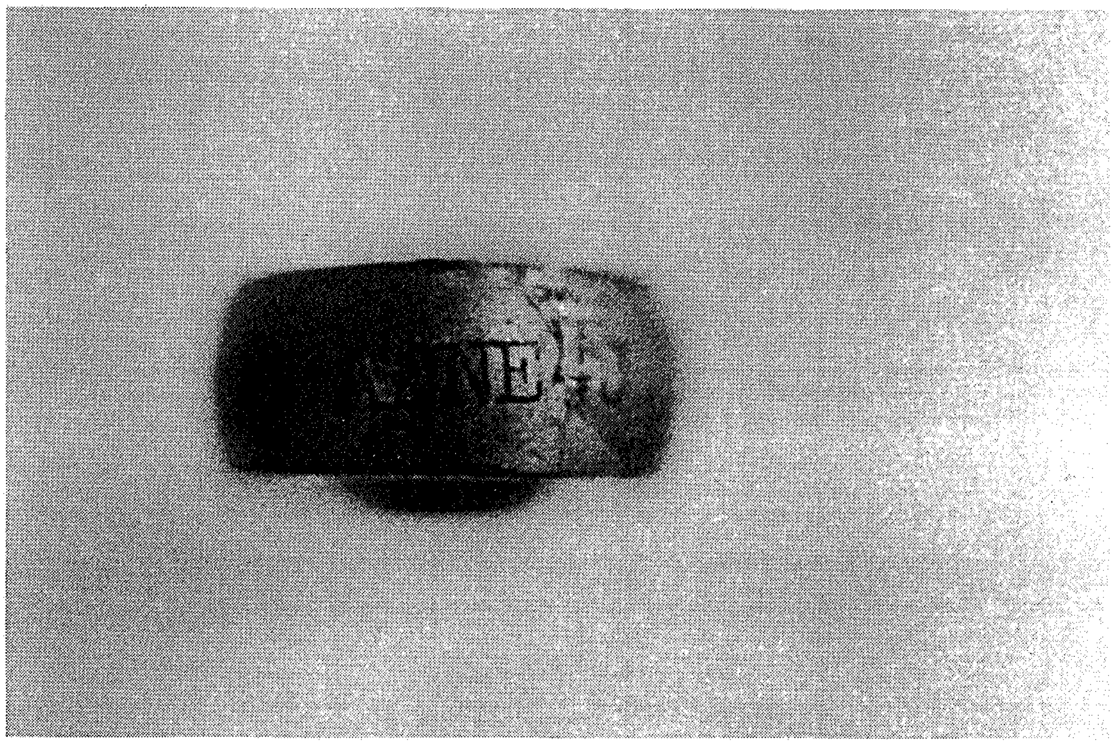
Photograph No. 1

LDEF Bearings as received and comparison sample bearings. SS and LS designate shank lengths only for subsequent reference. Note loss of chromate coating compared to new item. Indentation on rod and eye is Rockwell mark, required for MS rod end bearings.

d

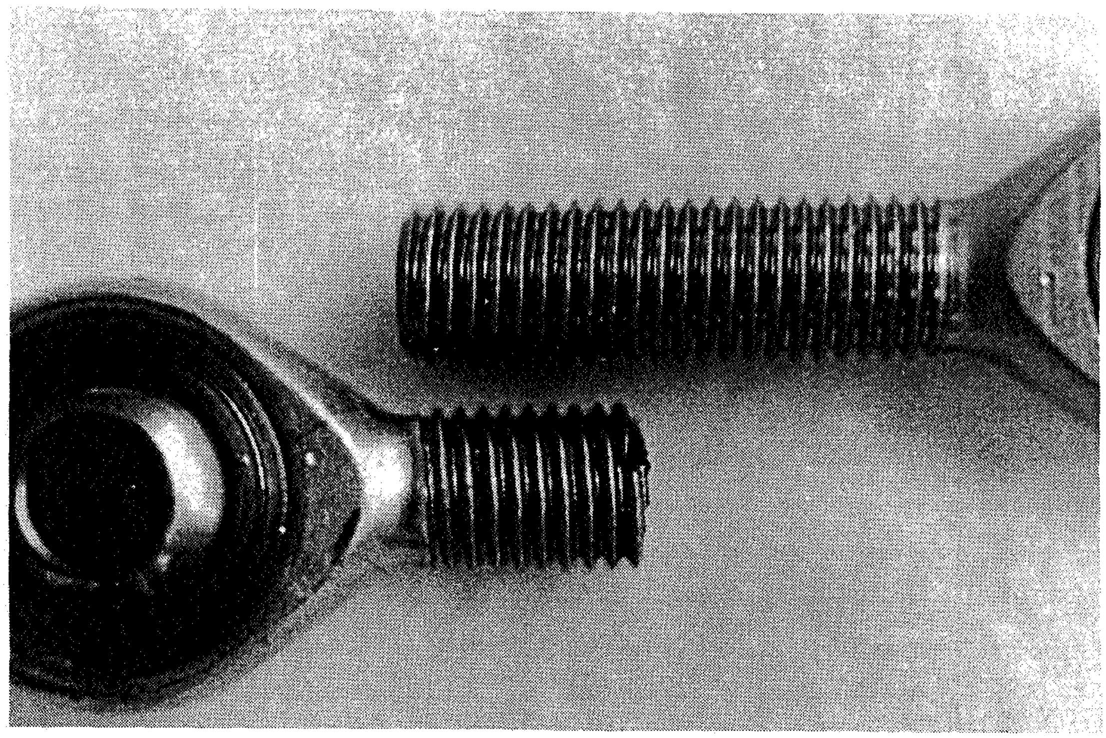


Photograph No. 2
Head end of short shank (SS) bearing showing part number, electrochemically etched. Note only partial loss of chromate coating.

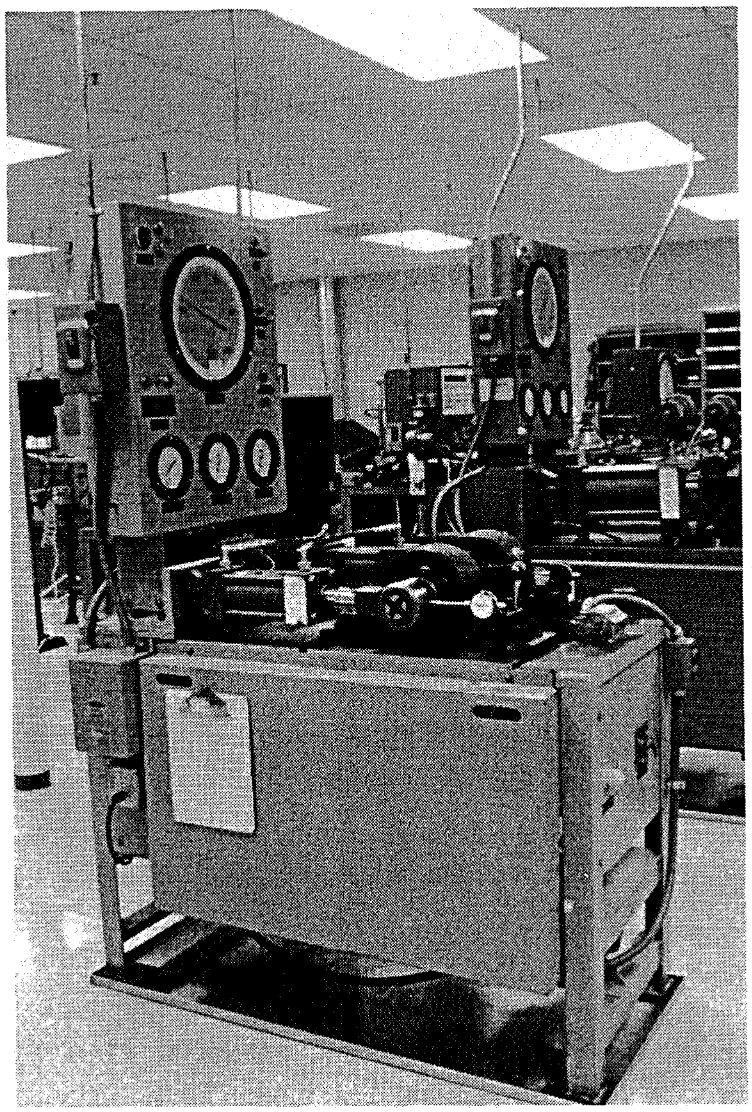


Photograph No. 3

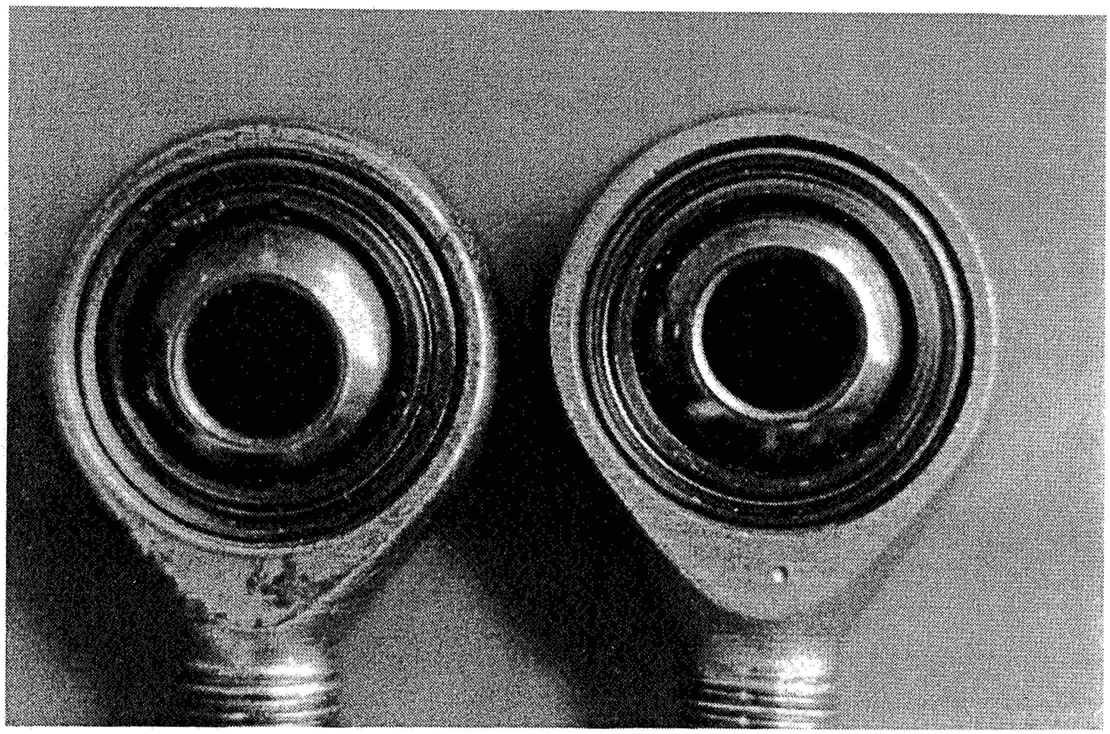
Head end of long shank (LS) bearing showing part number, electrochemically etched. Less chromate coating loss than on SS bearing in this area.



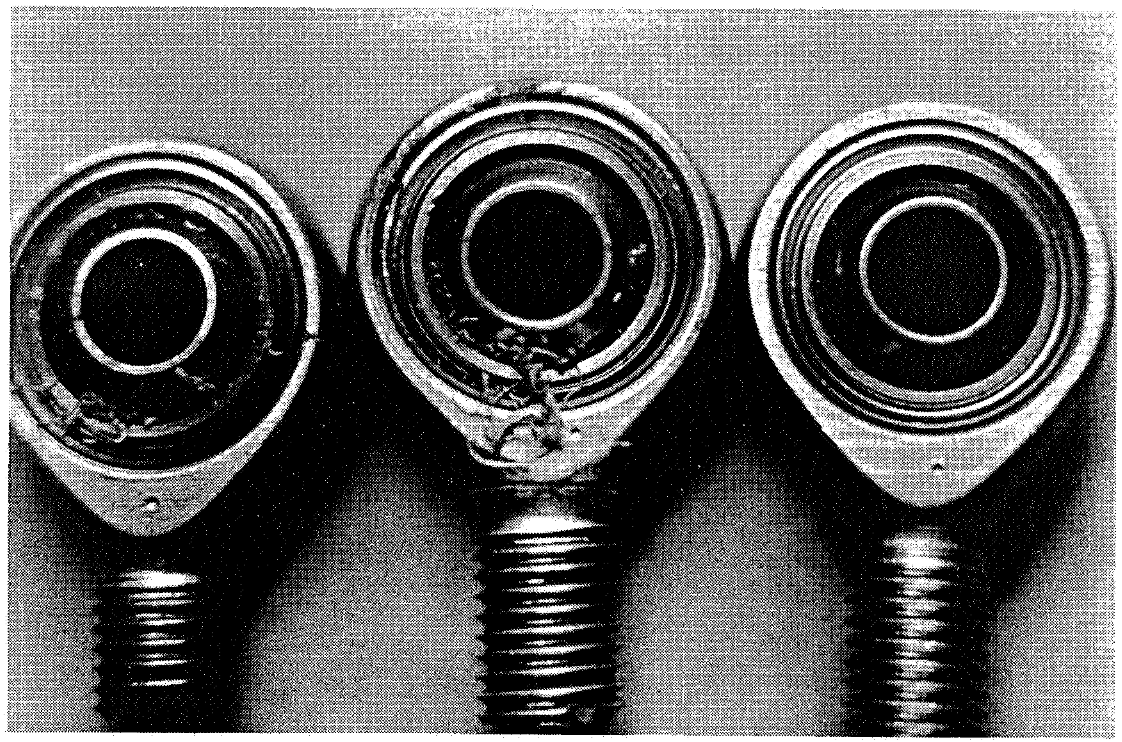
Photograph No. 4
Close-up *of* LS bearing shank compared with new part shank. Again, chromate loss is apparent.



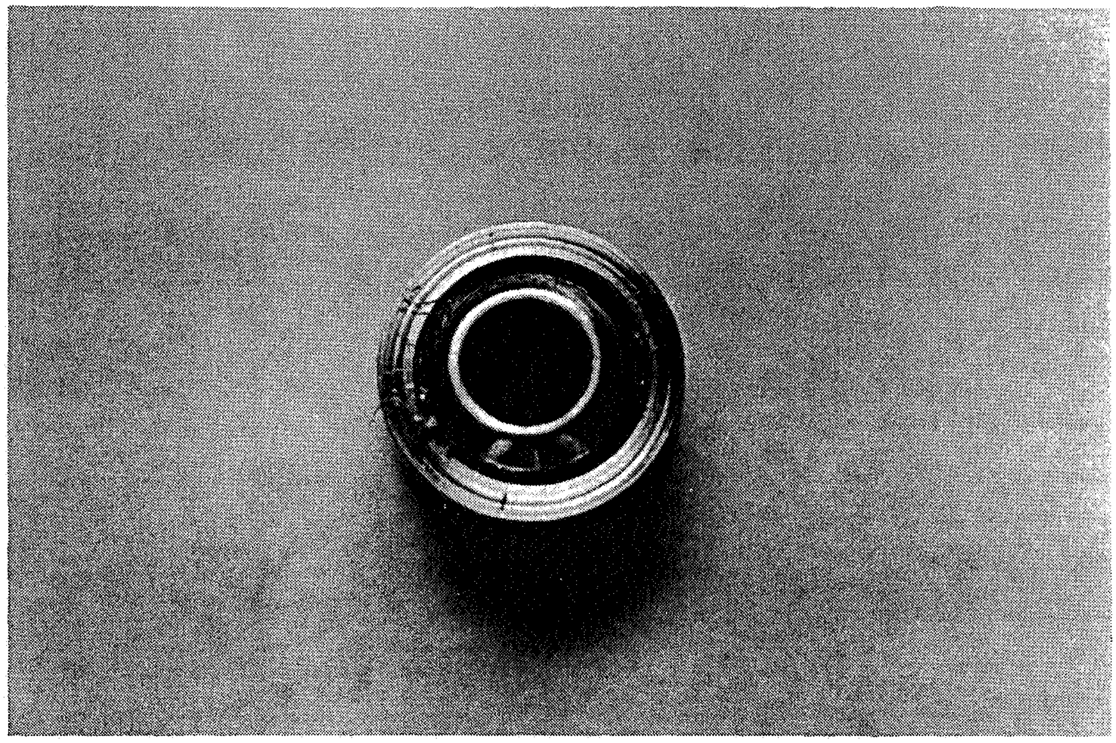
Photograph No. 5
Oscillating load bearing test machine, two stations, 20,000 lbsf/station load capacity. Used to test LDEF and reference bearings.



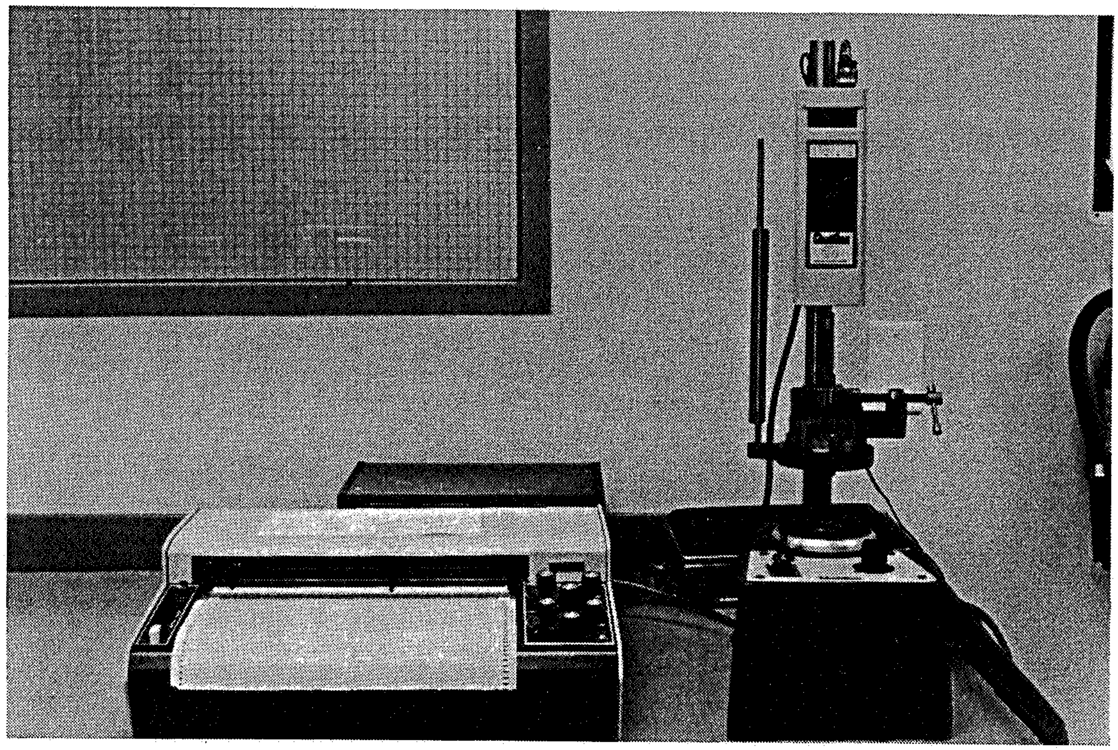
Photograph No. 6
Close-up of LDEF rod end bearing head and new reference bearing prior to doing oscillating load test on LDEF bearings. LDEF part shown is short shank (SS) bearing.



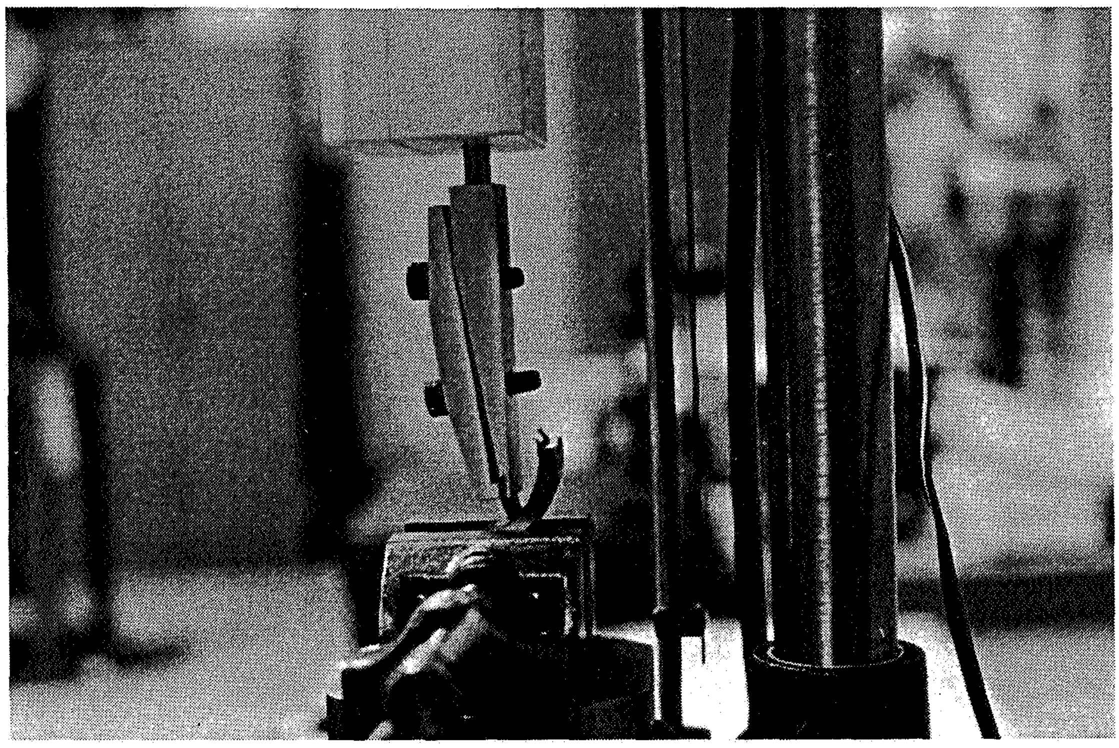
Photograph No. 7
LDEF bearings after oscillating load test with reference bearing (not tested). Note wear debris. Presence of such debris does not indicate bearing failure. The short shank (SS) bearing was loaded in tension at one-half MS load, then loaded to full MS load in compression. The long shank (LS) bearing was tested at full MS load in compression, the unloaded side used for liner peel test.



Photograph No. 8
Astro ADW4V spherical bearing after oscillating load testing. Again, note wear debris. The Astro ADW4V spherical bearing is that specified for the ADNE4J rod end bearing.

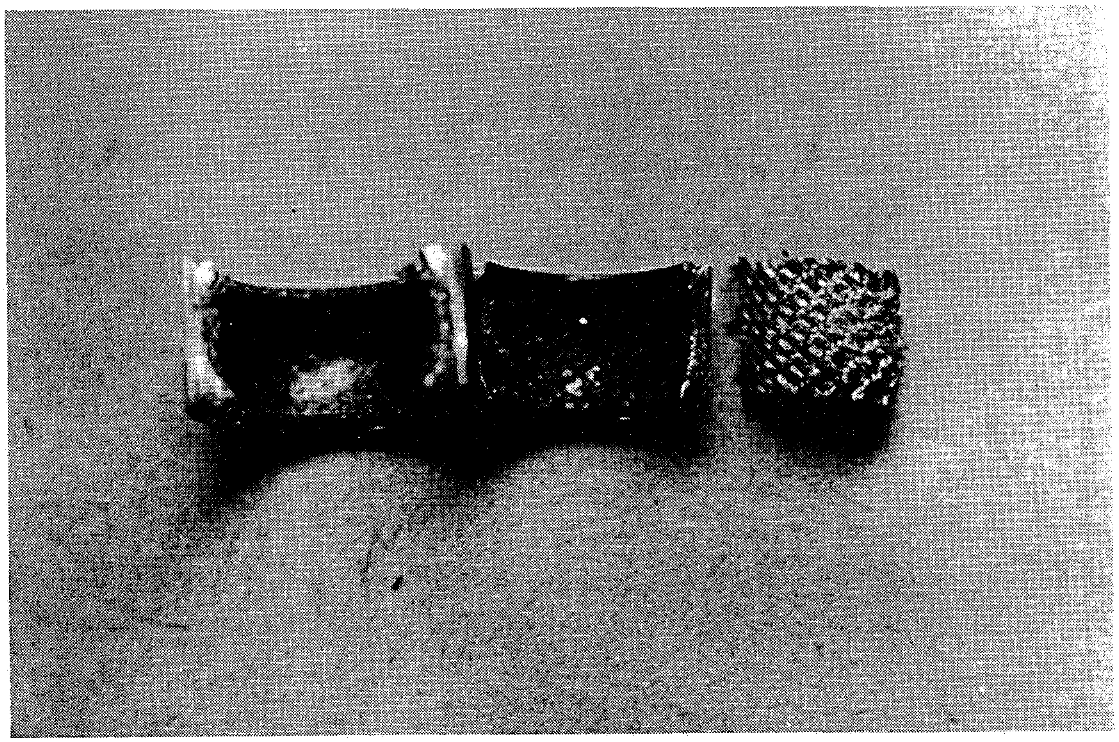


Photograph No. 9
Liner peel strength test set-up, consisting of a movable loading table, force gage and strip recorder.



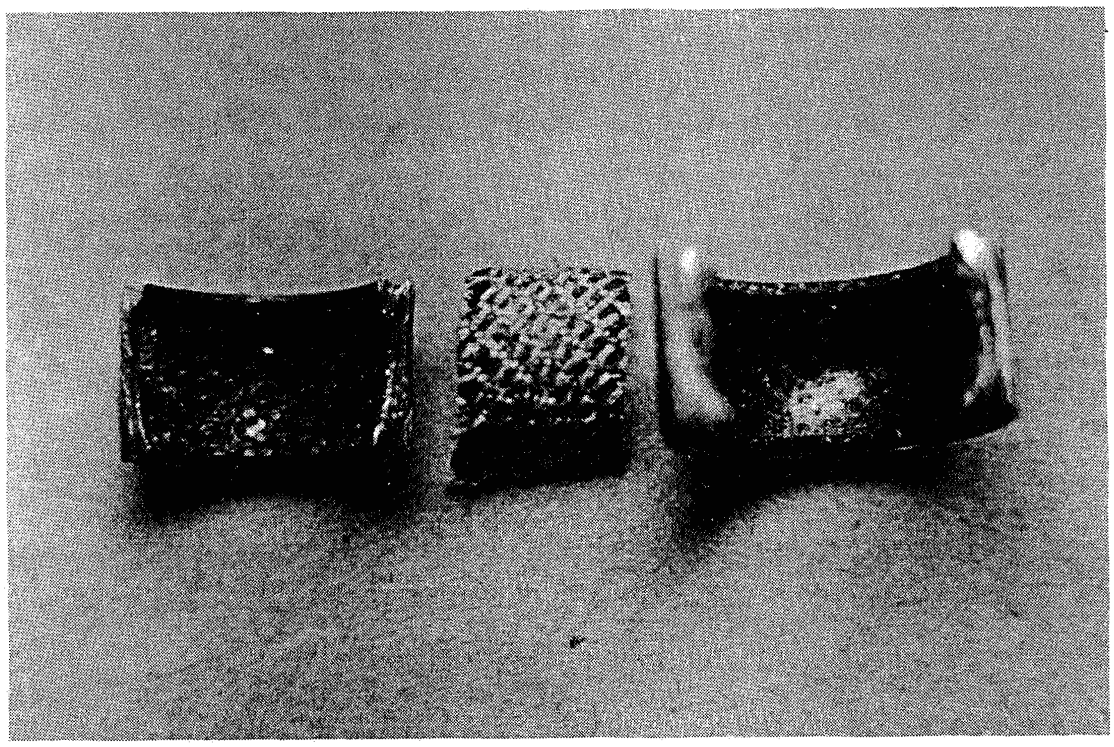
Photograph No. 10

Close-up of specimen undergoing peel test. Race section is held in a vise and a grip clamps on one end of the liner. Movable loading tables move down peeling the liner off the race section.



Photograph No. 11

Astro ADW4V peel test specimen showing liner face, lines adhesive bond inierface and rear surface of peeled liner.



Photograph No. 12

Astro LDEF bearing, ADNE4J (SS) test specimen showing liner face, liner adhesive grid interface and rear surface of peeled liner.

APPENDIX D
TEST DATA SHEETS

DATE ______________
MEMO NO.: ___________

TO: W. L. Plagemann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION: Apiezon-H Grease

MANUFACTURER & LOCATION

MATERIAL/PART: From inside surface of radiator from LDEF

APPLICABLE SPECIFICATION:

CURE CYCLE

Labor for the above test is to be charged to ______________________

SIGNATURE: ____________________

TO: J. Golden

DATE: 4-18-91

GROUP:

exposure time: 7days

SUBJECT: In Response to Above Request

The TML/VCM determination was controlled to the following paramenters.
Sample bar temperature = 125 ±1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1 °C (77 ± 2°F); Vacuum = 10^{-6} TORR; Exposure = ~~24 hours~~. The samples were equalibrated at 50% relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	% CVCM
0.022002	0.000478	.000150	2.17	0.68
0.027258	0.000671	.000171	2.46	0.63
		AVERAGE:	2.32	0.66

PREPARED BY: Gary Tamura

APPROVED BY: [signature]

DATE: ________________
MEMO. NO.: ____________

TO: W. L. Plagemann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance **with** SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION: Apiezon J

MANUFACTURER & LOCATION Control

MATERIAL/PART:

APPLICABLE SPECIFICATION:

CURE CYCLE

Labor for the above test **is** to be charged to________________________

SIGNATURE: ____________________

TO: Bruce Keough 3H-26 **DATE:** 10-16-91

GROUP:

SUBJECT: In Response to Above Request 7 day exposure

The TMLNCM determination **was** controlled to the following paramenters:
Sample bar temperature = 125±1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1 °C (77 ± 2°F); Vacuum = 10^{-6} TORR; ~~Exposure = 24 hours~~. The samples were equalibrated at **50%** relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	% CVCM
0.137450	0.001223	0.000705	0.90	0.51
0.107605	0.001114	0.000704	1.04	0.65
		AVERAGE:	0.97	0.58

PREPARED BY: Gary Tamas **APPROVED BY:** [signature]

DATE: ________________
MEMO NO.: ____________

TO: W. L. Plagemann 73-09

SUBJECT NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION: Apiezon H grease

MANUFACTURER & LOCATION:

MATERIAL/PART: From LDEF

APPLICABLE SPECIFICATION:

CURE CYCLE

Labor for the above test is to be charged to ________________________

SIGNATURE: ____________________

TO: Bruce Keough 3H-26

DATE: 7-11-91

GROUP:

SUBJECT: **In Response to Above Request** 24 hr exposure

±

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	% CVCM
0.044556	0.000583	0.000190		
0.033341	0.000506	0.000146	1.52	0.44
		AVERAGE:	1.42	0.44

PREPARED BY: Gary Tomas **APPROVED BY:** [signature]

DATE:________________
MEMO NO.:___________

TO: W. L. Plagemann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following part/material:

PRODUCT DESIGNATION: APIEZON GREASE "H" CONTROL

MANUFACTURER & LOCATION

MATEW A R T :

APPLICABLE SPECIFICATION

CURE CYCLE

Labor for the above test is to be charged to________________________

SIGNATURE: ____________________

TO: Bruce Keough 3H-26

DATE: 10-3-91

GROUP:

SUBJECT: In Response to Above Request 24 hr exposure

The TML/VCM determination was controlled to the following paramenters:
Sample bar temperature = 125 ± 1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1 °C (77 ± 2°F);
Vacuum = 10^{-6} TORR; Exposure = 24 hours. The samples were equalibrated at 50% relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	%CVCM
0.059561	0.000326	0.000117	0.55	0.20
0.114620	0.000579	0.000186	0.51	0.16
		AVERAGE	0.53	0.18

PREPARED BY: Gary Tamar APPROVED BY: [signature]

DATE: ________________
MEMO NO.: ___________

TO: W. L. Plagemann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION: Apiezon H CONTROL

MANUFACTURER & LOCATION: EXPOSED TO

MATERIAL/PART: 2 Days @ 100% Humidity

APPLICABLE SPECIFICATION prior to

CURE CYCLE: outgas testing

Labor for the above test is to be charged to________________________

SIGNATURE: ____________________

TO: Bruce Keough 3H-26

DATE: 10-23-91

GROUP:

SUBJECT: In Response to Above Request

The TML/VCM determination was controlled to the following paramenters: 24 hr exposure
Sample bar temperature = 125±1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1 °C (77 ± 2°F); Vacuum = 10^{-6} TORR; Exposure = 24 hours. The samples were equalibrated at 50% relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	%CVCM
0.100558	0.000678	0.000218	0.67	0.22
0.176071	0.001333	0.000330	0.76	0.19
		AVERAGE:	0.72	0.21

PREPARED BY: Gary Tomme

APPROVED BY: [signature]

DATE:________________
MEMO NO.:____________

TO: W. L. Plagernann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION: Apiezon H Grease CONTROL

MANUFACTURER & LOCATION: EXPOSED TO 21 days @ 100% Humidity

MATERIALPART: prior to outgas

APPLICABLE SPECIFICATION: testing

CURE CYCLE:

Labor for the above test is to be charged to________________________

SIGNATURE. ____________________

TO: Bruce Keough 82-32

DATE: 11-14-91

GROUP:

SUBJECT. **In Response to Above Request**

24 hr exposure

The TML/VCM determination was controlled to the following paramenters:
Sample bar temperature = 125 ±1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1 °C (77 ± 2°F); Vacuum = 10^{-6} TORR; Exposure = 24 hours. The samples were equalibrated at 50% relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	%CVCM
0.078308	0.001179	0.000233	1.51	0.30
0.110486	0.001379	0.000219	1.25	0.20
		AVERAGE:	1.38	0.25

PREPARED BY: Gary Tamar **APPROVED BY:** W Plag

4

DATE:

MEMO NO.:

TO: W. L. Plagemann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION APIEZON GREASE

MANUFACTURER & LOCATION "L" CONTROL

MATERIAL PART:

APPLICABLE SPECIFICATION

CURE CYCLE

Labor for the above test is to be charged to

SIGNATURE:

TO: Bruce Keough 3H-26

DATE: 10-3-91

GROUP:

SUBJECT: In Response to Above Request

The TML/VCM determination was controlled to the following paramenters: 24 hrs exposure
Sample bar temperature = 125 ± 1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1 °C (77 ± 2°F); Vacuum = 10^{-6} TORR; Exposure = 24 hours. The samples were equalibrated at 50% relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	% CVCM
0.179405	0.000086	0.000048	0.05	0.03
0.114518	0.000117	0.000049	0.10	0.04
		AVERAGE	0.08	0.04

PREPARED BY: Gary Tamar APPROVED BY: [signature]

DATE:

MEMO.NO.:

TO: W. L. Plagemann 73-09

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine VCM and TML properties in accordance with SP-R-0022A for the following part/material:

PRODUCT DESIGNATION:

MANUFACTURER & LOCATION: Apiezon L Control

MATERIALPART:

APPLICABLE SPECIFICATION:

CURE CYCLE

Labor for the above test is to be charged to

SIGNATURE:

TO: Bruce Keough 3H-26

DATE: 10-16-91

GROW.

SUBJECT: In Response to Above Request 7day exposure

The TML/VCM determination was controlled to the following paramenters:
Sample bar temperature = 125 ±1 °C (257 ± 2°F); Collection plate temperature = 25 ± 1°C (77 ± 2°F); Vacuum = 10^{-6} TORR; ~~Exposure = 24 hours.~~ The samples were equalibrated at 50% relative humidity for 24 hourts prior weighing.

SAMPLE WEIGHT (g)	SAMPLE WEIGHT LOSS (g)	COLLECTOR PLATE WEIGHT GAIN (g)	% TML	%CVCM
0.140173	0.000 290	0.000213	0.21	0.15
Cup	over Turned	during experiment		
		AVERAGE:	0.21	0.15

PREPARED BY: Gary Tamer

APPROVED BY:

TO: **W. L. Plagemann** **73-09**

DATE:________________
MEMO NO.:____________

SUBJECT: NASA SP-R-0022A Outgassing Test

Please determine **VCM** and TML properties in accordance with SP-R-0022A for the following padmaterial:

PRODUCT DESIGNATION: APIEZON L CONTROL

MANUFACTURER & LOCATION: EXPOSED TO 2

MATERIAL/PART: 100% HUMIDITY PRIOR TO

APPLICABLE SPECIFICATION: OUTGAS TESTING

CURE CYCLE

Labor for the above test is to be charged **to**____________________

SIGNATURE: ____________________

TO: Bruce Keough 3H-26

DATE: 10-23-91

GROUP:

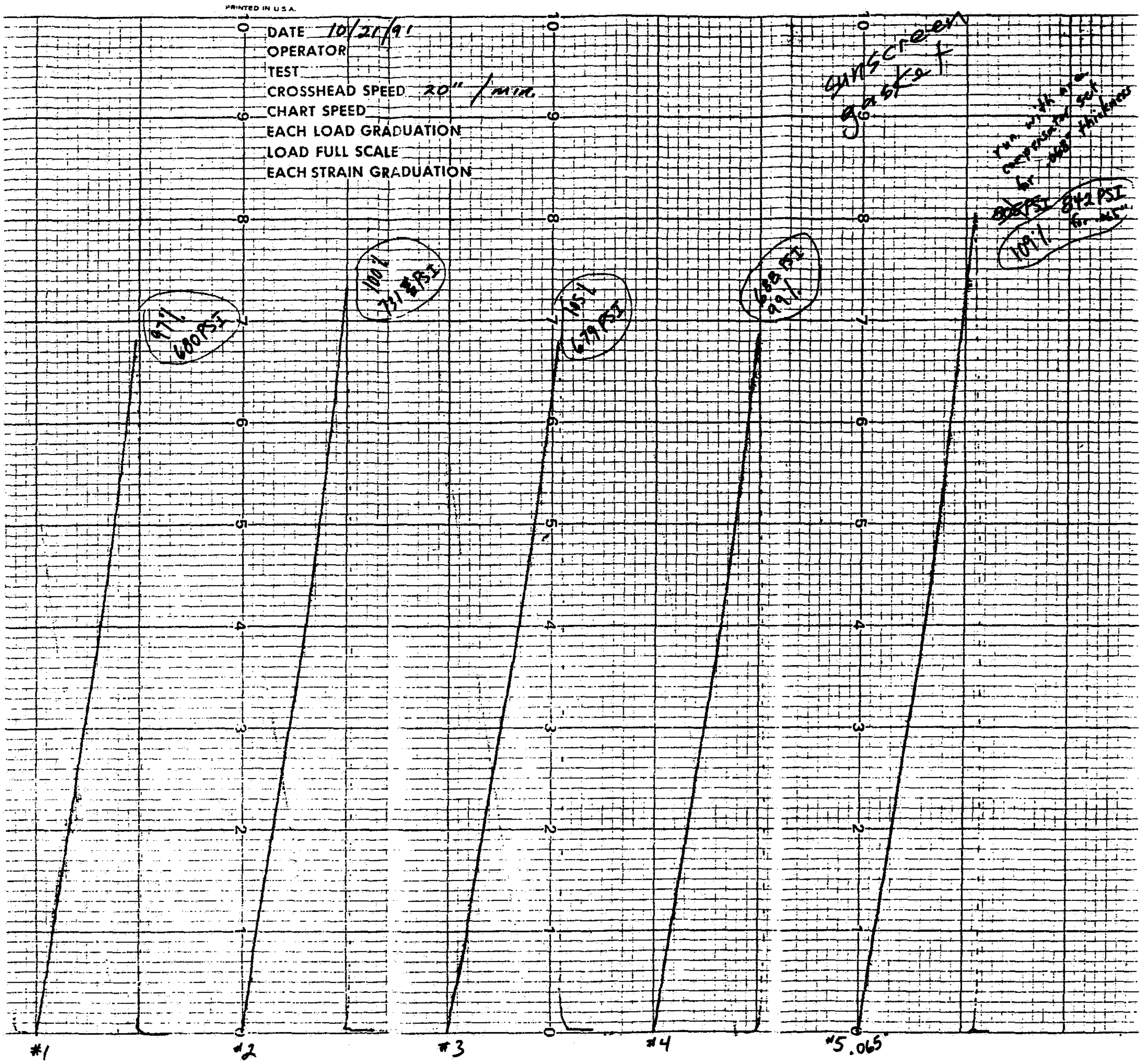
SUBJECT In Response to Above Request

The TML/VCM determination was controlled to the following paramenters:
Sample bar temperature **= 125±1 °C (257 ± 2°F);** Collection **plate** temperature **=** 25 **±** **1**°C **(77 ± 2°F);** Vacuum **= 10^{-6}** TORR; Exposure = ***24*** hours. The samples were equalibrated at **50%** relative humidity for ***24*** hourts prior weighing.

SAMPLE WEIGHT (g)	**SAMPLE WEIGHT LOSS (g)**	**COLLECTOR PLATE WEIGHT *GAIN* (g)**	**% TML**	**%CVCM**
.143609	0.001094	0.000059	0.76	0.04
.176303	material lost over edge of cup			
		AVERAGE:	0.76	0.04

PREPARED BY: Gary Tamm

APPROVED BY: [signature]



Experiment S0050 silicone rubber tensile testing results

a

REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*

This report described results from testing and analysis,of seals and lubricants subsequent to the 69-month low-Earth-orbit (LEO) exposure on the Long Duration Exposure Facility (LDEF). Results show that if the materials were shielded from exposure to LDEF's external environment, the 69-month exposure to LEO resulted in minimal changes to material properties. However, if the materials were exposed to LDEF's exterior environments (atomic oxygen, solar radiation, meteoroids, and/or space debris) a variety of events occurred, ranging from no material change, to changes in properties, to significant erosion of the material.

14. SUBJECT TERMS
Cow Earth Orbit, LDEF, Seals, Lubricants, Atomic Oxygen, Friction, Galling, Coldwelding

112

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