# Volume I: ITA/I Report

## 1.0 Notification Letter (from NESC Review Board Chairman to stakeholders)

## 2.0 Signature Page (Assessment Team Members)

A signature page denotes that the signatories certify that the information contained herein is true to the best of their knowledge. Refer to Page iii for the Assessment Signature Page.

## 3.0 List of Team Members

| Name/Affiliation | Discipline |
|---|---|
| Paul Munafo, NESC | Team Leader; Materials |
| Phillip Hall, NESC | Alternate Team Leader; Tribology |
| Edward Devine, Swales | Tribology; Structures |
| Michael Dube, Independent Consultant | Tribology; Chemistry |
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## 4.0 Executive Summary

Disassembly inspection of the OV-103 Rudder/Speed Brake (R/SB) actuators revealed corrosion, pitting, and wear to varying degrees, along with degradation of the lubricant, Braycote 601. A program decision was made to replace the actuators in OV-103 with the existing spares, a single ship set which had been in controlled storage for the past 17 years. This assessment was performed to address the following two issues, which had been raised within the Program Control Review Board process:

Issue 1. Grease separation into its component oil and thickener is known to occur in storage. Its effect on lubricity is not known.

Issue 2. Chemical reactions involving the grease and the gear/housing material, 9310 steel, could lead to formation of Lewis acids, resulting in corrosion, pitting, and cracking.

Issue 1 was addressed directly by performing lubricity testing using aged and separated grease obtained from several sources, including grease that had been removed from the OV-103 actuators. Three test protocols were used: (1) Falex Block on Ring; (2) Spiral Orbit Tribometer (SOT); and (3) Wedeven Associates Machine (WAM) testing. In all cases, no detrimental effect on lubricity was observed due to aged and/or separated grease.

Issue 2 was addressed in three ways: (1) an extensive Literature Review; (2) WAM testing to duplicate the conditions observed in the OV-103 R/SB actuators; and (3) Metallurgical Thermodynamic analysis, using Thermal Gravimetric Analysis (TGA), to bound the amount of degradation that might occur during 17 years of controlled storage. The Literature Review revealed that absent tribological action and the resulting wear particles, no corrosion should occur below 190$^{o}$C. The WAM testing was successful in duplicating the pitting/corrosion effects observed on OV-103 by high frequency low amplitude wear testing, thus reinforcing the results reported in the literature for similar material/lubricant combinations. The TGA testing and thermodynamic analysis predicted no significant corrosive effects from static, controlled storage for 17 years.

It was concluded by the NESC and recommended to the Shuttle Program that the spare R/SB actuators removed from storage after 17 years were safe to use on OV-103.

# 5.0 Plan

## Background

During the removal of the Body Flap (BF) actuators from the Space Shuttle Discovery, Orbiter OV-104, several bushings were damaged. Upon return to the vendor, Hamilton Sundstrand (HS), excessive *external* corrosion of the 9310 steel ring gear housings was noted.

Disassembly inspection revealed extensive *internal* corrosion, including gear tooth pitting. It was also observed that grease separation had occurred. The corrosion and pitting became a flight concern and the BF actuators from Orbiter OV-103 were returned to HS. Corrosion and pitting were observed again in the OV-103 hardware. Housings were reworked and four BF actuators were built, tested, and returned to the fleet.

Because of the similarity of design to the BF actuator, the R/SB actuators from OV-103 were removed and returned to HS for disassembly, examination and refurbishment. No R/SB actuators had been disassembled since 1983. In all cases, examination of the four actuators revealed corrosion, pitting, and wear to varying degrees. Some degradation of the lubricant, Braycote 601, was also noted. Refer to Figure 5.0-1.

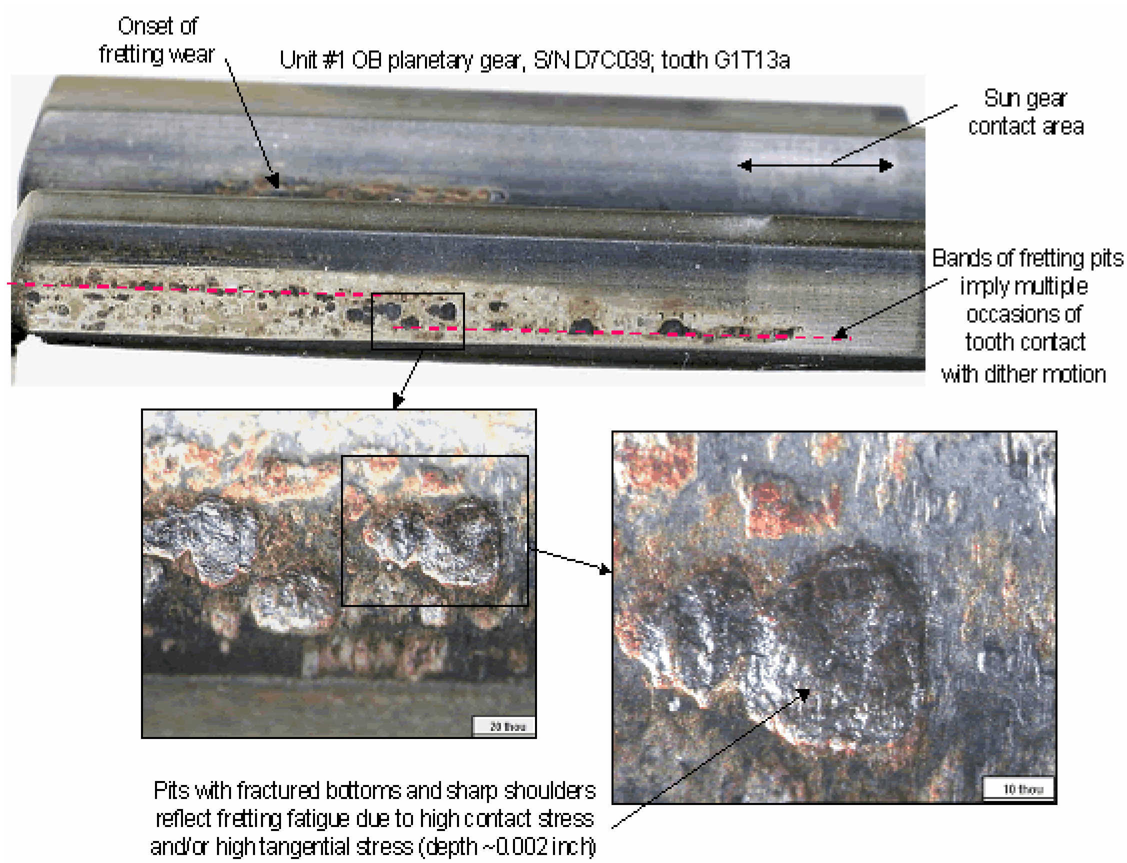



**Figure 5.0-1. Severe Fretting Wear Damage on R/SB Planetary Gear**

A decision was made to replace the actuators in OV-103 with the existing spares, a single ship set which had been in controlled storage at the KSC, including individual desiccated cans, for the past 17 years. These spares underwent acceptance testing in 2003; their torque efficiencies were above minimum requirements and comparable to the original values recorded in 1986.

There is no precedent for using actuators that have been in storage for 17 years. The following two issues were raised through the orbiter Problem Resolution Team (PRT) process, both involving the condition of the grease in the spare actuators:

Issue 1. Grease separation into its component oil and thickener is known to occur in storage. Its effect on lubricity is not known.

Issue 2. Chemical reactions involving the separated grease and the gear/housing material, 9310 steel, could lead to formation of Lewis acids, resulting in pitting, corrosion, and cracking.

The debate within by the PRT was sharp and the differences could not be reconciled. The Shuttle Program Manager asked the NESC to help resolve these issues.

**Approach**

Issue 1 was addressed directly. The grease retrieved from the OV-103 actuators provided one source of test material, and several containers of *old* Braycote grease were also available. Furthermore, standard test protocols exist for evaluating lubricity. Three of these test methods were used to evaluate the effects of long-term storage on the lubricity of Braycote 601: (1) Falex Block on Ring Testing, per ASTM 3704; (2) Spiral Orbit Tribometer Testing, which was first described in NASA TP 3629, October 1996; and (3) WAM Testing.

Issue 2 could not be addressed directly, as there is no standard test protocol for accelerated corrosion testing involving products from chemical degradation of lubricants acting on a substrate material. A Literature Review, which was initiated early in this program, provided insight into the corrosion issue. It was determined that previous studies of corrosion involving formation of Lewis acids with similar lubricants and substrate materials required some form of tribological action to initiate the corrosion. Furthermore, it was observed that the corrosion ceased once the worn-off material was depleted, suggesting that even if the corrosion could be initiated under storage conditions, it would be self-limiting. The Literature Review also suggested that a thermodynamic approach, using TGA to determine rate constants and activation energies, might provide further insight into the extent of corrosion damage that might exist in the actuators that were in controlled storage for the past 17 years. Based on the Literature Review, two experimental test studies were undertaken to gain insight into the corrosion issue, as follows:

1. **WAM Testing.** Attempt to duplicate the corrosion observed in the OV-103 gears.

2. **TGA Testing.** Develop a fundamental understanding of the corrosion mechanics.

The following section summarizes the research that was performed to resolve the two issues described above: the Literature Review, which provided insight into both issues; Falex Block on Ring testing, Spiral Orbit Tribometer testing, and WAM testing, to evaluate the lubricity of 17-year old separated grease; and, WAM and TGA testing, that were performed to understand the mechanism that caused the corrosion observed in OV-103 and to determine the propensity for corrosion under the static condition of 17 years in storage.

# 6.0 Analysis and Testing

## 6.1 LITERATURE REVIEW

The literature reviewed during this Program is listed in Appendix A, in alphabetical order of the principal author.

**Background**

Flight vehicles have required active control of aerodynamic surfaces since their inception. These surfaces control the vehicle's attitude and direction while encountering aerodynamic forces. These surfaces are operated by a series of hydraulic actuators of various designs. For conventional aircraft, these actuators are lubricated with standard terrestrial greases based on organic ester and hydrocarbon technology. In addition, these greases are fortified with a variety of additives, which enhance their performance and longevity under atmospheric conditions. These actuators, which undergo thousands of cycles a year, undergo routine maintenance every three to five years, depending on usage.

The Space Shuttle Orbiters also require control of their aerodynamic surfaces after re-entry into the earth's atmosphere. Each orbiter has a complement of eight actuators that move the vehicle's body flap, rudder and speed brake. The four actuators used for the body flap use a geared rotary design based on case carburized 9310 steel gears and 52100 steel bearings. A similar, but not identical, design is used for the four R/SB actuators. Since these components experience both atmospheric and vacuum conditions, including high humidity and a range of temperatures, conventional grease lubrication is not used. Instead, a synthetic perfluoropolyether (PFPE) grease, thickened with a polytetrafluoroethylene polymer (PTFE), is employed. This grease also contains a corrosion inhibitor, dimethyloctyldecylbenzyl ammonium bentonite, and an antirust compound, sodium nitrite. This lubricant was commercially known as Braycote 601 and the current environmentally friendly version is Braycote 601EF, both distributed by Castrol Industrial North America. The linear PFPE base oil is a random copolymer of perfluorinated ethylene oxide and perfluorinated methylene oxide produced in Italy by Solvay Solexis, formally Ausimont, using the UV catalyzed photo-oxidation of tetrafluoroethylene (Sianesi et al, 1973); it is marketed under the trade name Fomblin Z-25 (aka 815Z). This material has been the lubricant of choice for the space program for over 30 years (Jones, 1995).

### Lubricant Chemistry

PFPE liquid lubricants are used in space applications for a variety of reasons. Being fully fluorinated and, therefore, containing no carbon hydrogen bonds, they are not susceptible to oxidation. Therefore, they can be operated in oxidizing environments to temperatures of 288C

(Jones, Paciorek, Ito and Kratzer, 1983). In non-oxidizing, or in vacuum environments, they are thermally stable to 370C to 380C (Helmick and Jones, 1992A). They also have a wide liquid range and good elastohydrodynamic film forming capability, and they are optically transparent over a wide range of wavelengths. Therefore, these materials, in the form of greases, are ideally suited for applications, such as the orbiter actuators, which involve wide variations in temperature, exposure to both atmospheric and vacuum conditions, a minimal number of duty cycles, years of storage time and years before refurbishment.

### Lubricant Tribology

As stable as these PFPE materials are under static conditions in glassware, they, like their conventional counterparts, are readily degraded in lubricated (tribological) contacts, particularly at the high Hertzian stresses that occur in the concentrated contacts of ball bearings and gears. In fact, under these conditions they are even more prone to degradation than conventional hydrocarbon or ester based lubricants. For example, Vacuum Spiral Orbit Tribometry (Pepper and Kingsbury, 2003B) has shown that the relative lifetime of Fomblin Z-25 in contact with a standard bearing steel (52100) and with 440C stainless steel (Jansen, Jones, Predmore and Loewenthal, 2001) is two orders of magnitude lower than a hydrocarbon based space lubricant (Pennzane). This difference in lifetime has also been confirmed in full-scale vacuum bearing tests (Loewenthal, Jones and Predmore, 1999).

### Lewis Acid Catalysis

Many studies have demonstrated that PFPE molecules are very susceptible to degradation in the presence of Lewis Acids (electron acceptors) (Carré and Markovitz, 1985; Kasai, 1992; Herrera-Fierro et al, 1993; Paciorek and Kratzer, 1994 and Morales, 1994). Although there is conjecture as to what exact chemical mechanism is taking place, it is obvious that during the tribological process, the PFPE degradation products can and do react with ferrous alloys (Zehe and Faut, 1990; Carré, 1986; and Mori and Morales, 1989A) producing a catalytic surface of metallic fluorides, oxyfluorides and organic degradation products. Nevertheless, it is these series of reactions that produce surface films that prevent galling or scuffing and reduces friction, thus effecting the boundary lubrication process (Masuko, Jones and Helmick, 1993 and Dekoven and Meyers, 1991).

### Detection of PFPE Degradation

During and after a PFPE has been stressed in a tribological contact, chemical markers are present that can be detected by various analytical techniques. Iron fluoride and oxyfluorides have been detected by X-ray Photoelectron Spectroscopy (XPS) (Herrera-Fierro et al, 1993 and Carre, 1986). Hydrogen bonded OH groups and carboxylic acid species were detected by Fourier Transform Infrared Spectroscopy (FTIR) (Herrera-Fierro et al, 2000). In addition, reaction of a

PFPE at 350C with iron fluoride yields similar products (acyl fluorides and ketones) also detected by FTIR (Carre and Markowitz, 1985).

In addition to these chemical markers, some PFPE degradation is accompanied by chain scission, which results in a decrease in the average molecular weight. This can be readily detected by Size Exclusion Chromatography (SEC) using either High Performance Liquid Chromatography/Gel Permeation Chromatography (HPLC/GPC) using a Freon 113 mobile phase (Morales, 1986 and Kasai, 1992), or using Super Critical $CO_2$ Chromatography (SCF) (Aerospace Corp).

### Tribological Testing

There are a variety of test devices that can be used to measure the tribological performance of a grease. These include pure sliding devices such as Block on Ring (Jett et al, *Second Aerospace Environmental Tech. Conf*, March, 1997), rolling contact simulators such as Spiral Orbit Tribometry (Pepper and Kingsbury, 2003A) and WAM tribometers (Wedeven, 2001).

### Surface Chemistry

Careful surface analytical studies have been performed on Fomblin Z25 in contact with various surfaces (Herrera-Fierro et al, 1993). It was concluded that gold surfaces were unreactive towards Fomblin Z-25 at any temperature. Heating simply led to evaporation of unchanged lubricant. A ferrous alloy (440C stainless steel) showed no reactivity at room temperature, but heating to 190C initiated some fluid degradation, forming a debris layer at the liquid/metal interface. This layer, when fully formed, acted as a passivation layer preventing further degradation of the fluid remaining on the top. In contrast, a clean aluminum surface reacts with Fomblin Z25 at room temperature causing lubricant degradation. The other important conclusion was that, in all cases, thermally or tribologically induced, the degradation of Fomblin Z25 resulted in the preferential consumption of the difluoroformyl or “acetal” carbon, also known as the weak link.

### Thermogravimetry

Thermal Gravimetric Analysis (TGA) (sometimes referred to as dynamic thermogravimetry) has been used for many years to study mass loss as a function of temperature for polymeric materials (Wendlandt, 1986). These mass-loss versus temperature curves can be related to thermal and/or thermal-oxidative stability, depending on the cover gas. Catalytic effects with metals can also be studied (Helmick and Jones, 1992B). In addition, this data can also be used to determine rate constants and energies of activation (Dube, See Section 6.3.2).

### Radiation Stability

All organic molecules are susceptible to damage by irradiation. Perfluoropolyethers have been reported to be degraded by low energy electrons (D'Anna et al, 1987), high energy electrons (Pacansky, Waltman and Wang, 1986) and by X-rays (Barnaba et al, 1966, and Mori and Morales, 1989B).

### CONCLUSIONS

1. Degradation of grease during controlled storage was unlikely. The only effect expected to occur under static conditions, less than around 190$^o$C, was separation into its component oil and thickener. While the effect of this separation on lubricity is unknown, standard experimental techniques are available to readily measure it.

2. Corrosion due to chemical reaction between the lubricant and the 9310 steel gear and housing material was unlikely during storage. The postulated chemical mechanism, involving the intermediate formation of Lewis acids, has only been observed in tribological applications, with the metallic wear products serving as a catalyst. The most promising diagnostic technique to further explore the possibility of corrosion during storage is TGA, using the actual gear material/lubricant combination.

## 6.2 LUBRICITY TESTING

### Background

Most of the tribological testing performed during the Program, using the Block on Ring, Spiral Orbit Tribometer or WAM mechanisms, required the ability to artificially separate the oil from the thickener. This was accomplished using ASTM Standard Test Method D6184-98, "*Oil Separation from Lubricating Grease (Conical Sieve Method)*", located in Appendix B of this report.

### 6.2.1 Falex Block on Ring Testing

### PROCEDURE

This testing was performed on a LFW-1 Friction and Wear machine (block on ring tester). This tester contains a 440C stainless steel ring rotating against a block of 440C stainless ring material. Surface velocity of the test ring was 7.9 m/min (26 ft/min), which corresponds to a spindle speed of 72 rpm. The test ring is made of 440C corrosion resistant steel having a Rockwell hardness of 56 to 58 HRC. These rings have a ground face 8.15 mm wide, with an outside diameter of 35 mm. The surface finish of the rings is from 0.223 to 0.381μmeter rms (9 to 15 μinch rms) in the direction of motion. The test block is made of 440C corrosion resistant steel with a test surface 6.35 mm by 15.76 mm long. A photograph of the contact surfaces is shown in Figure 6.2.1.-1.

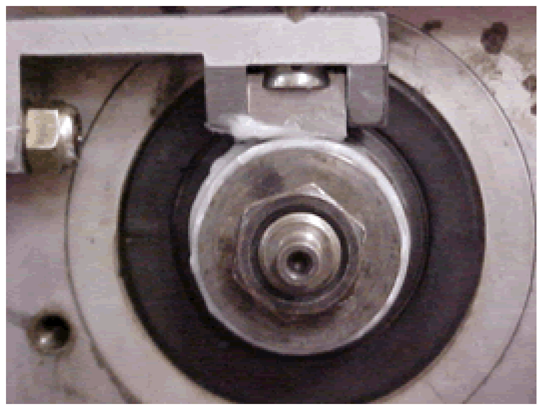


**Figure 6.2.1-1. Contact Surfaces, Falex Block on Ring Tester**

Testing was accomplished per ASTM D3704-96, *"Standard Test Method for Wear Preventive Properties of Lubricating Greases Using the (Falex) Block on Ring Test Machine in Oscillating Motion"*, which is located in Appendix C of this report.

To gain a significant number of test results (in view of the limited grease samples available), and also to obtain data on 601EF, the only lubricant currently available, the tribological properties of the following Braycote greases were evaluated:

- Braycote 600 (oil depleted)
- Braycote 600 (mixed)
- Braycote 601 (oil depleted)
- Braycote 601 (mixed)
- Braycote 601EF (oil depleted)
- Braycote 601EF (mixed)

Samples designated as "mixed" were obtained from virgin grease that was manually stirred to ensure no oil separation. Samples designated as "oil depleted" were obtained using Standard Test Method ASTM D6184-98. In this method, weighed samples of virgin grease (that has been manually stirred to ensure no oil separation) are placed in a cone-shaped wire cloth sieve, suspended in a breaker. The samples are heated under static conditions for a specified time and temperature. To increase the amount of oil separation, the time was 112 hours compared to the standard 30 hours and the temperature was 204C compared to the standard 10C. After the oil separation was complete, the separated oil was discarded, the oil depleted grease was collected and manually mixed, and the oil content of each mixture was measured prior to testing.

Test Method ASTM D3704 was used, with the following exceptions:

1. The machine was not used in the oscillation mode; instead, the motion was continuously rotated in the same direction at 72 rpm.
2. Due to the limited quantity of grease available, only one test load (150 lbs) was applied.
3. The samples were 440C corrosion resistant steel having hardness of 58 to 62 HRC.
4. The test was run until the onset of galling.

Three tests per mixture were performed. The coefficient of friction was continuously monitored and recorded by a computer during testing. After testing, the samples were ultrasonically cleaned and the wear scar of the block was measured using a Taly-surf profilometer.

### RESULTS

The results of the Falex Block on Ring are shown below in Table 6.2.1-1 and in Figures 6.2.1-2 through 6.2.1-5.

**Table 6.2.1-1. Block on Ring Testing at MSFC**

| | | | Coefficient of Friction | | | | Wear Depth (micrometers) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Alloy | Grease | # of Tests | test 1 | test 2 | test 3 | Average | test 1 | test 2 | test 3 | Average |
| 440C | Braycote 600 | 3 | 0.12 | 0.12 | 0.05 | 0.10 | 2.31 | 2.05 | 2.55 | 2.30 |
| 440C | Braycote 600(separated) | 3 | 0.12 | 0.08 | 0.10 | 0.10 | 1.81 | 1.70 | 1.60 | 1.70 |
| 440C | Braycote 601 | 3 | 0.10 | 0.10 | 0.10 | 0.10 | 2.00 | 2.50 | 2.40 | 2.30 |
| 440C | Braycote 601(separated) | 3 | 0.09 | 0.11 | 0.11 | 0.10 | 1.10 | 1.40 | 1.40 | 1.30 |
| 440C | Braycote 601EF | 3 | 0.12 | 0.09 | 0.08 | 0.10 | 2.07 | 3.21 | 2.10 | 2.46 |
| 440C | Braycote 601EF(separated) | 3 | 0.09 | 0.11 | 0.11 | 0.10 | 1.40 | 1.20 | 1.50 | 1.37 |
| 440C | Braycote 3l-38-RP | 3 | 0.10 | 0.08 | 0.11 | 0.10 | 1.97 | 2.20 | 1.85 | 2.01 |
| 9310 | Braycote 601 | 3 | 0.11 | 0.13 | 0.15 | 0.13 | 1.70 | 2.50 | 10.00 | 4.73 |
| 9310 | Braycote 601(separated) | 3 | 0.06 | 0.11 | 0.10 | 0.09 | 4.00 | 3.00 | 2.70 | 3.23 |
| 9310 | Braycote 601EF | 3 | 0.11 | 0.10 | 0.13 | 0.11 | 2.20 | 2.60 | 6.00 | 3.60 |
| 9310 | Braycote 601EF(separated) | 3 | 0.13 | 0.10 | 0.13 | 0.12 | 2.60 | 4.80 | 2.20 | 3.20 |

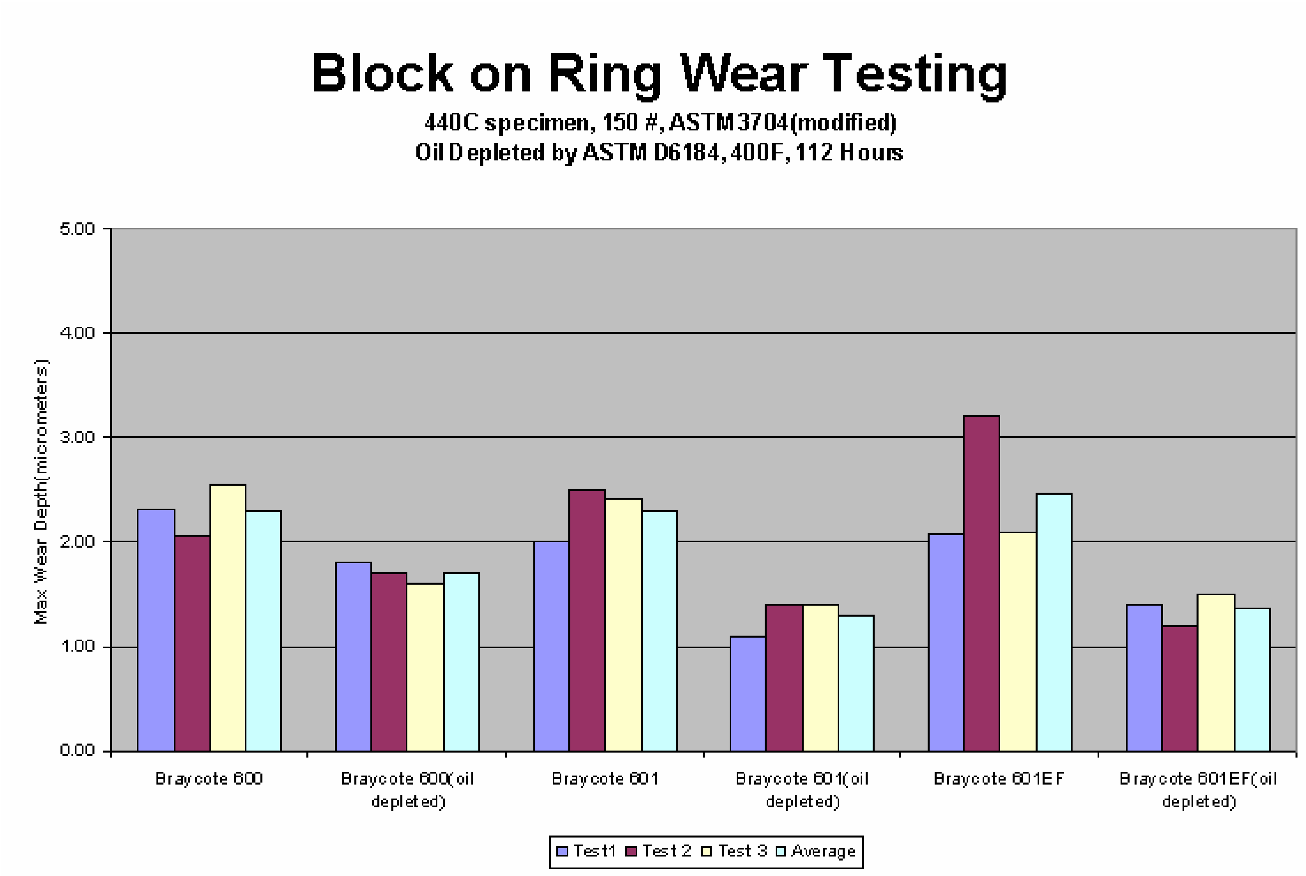
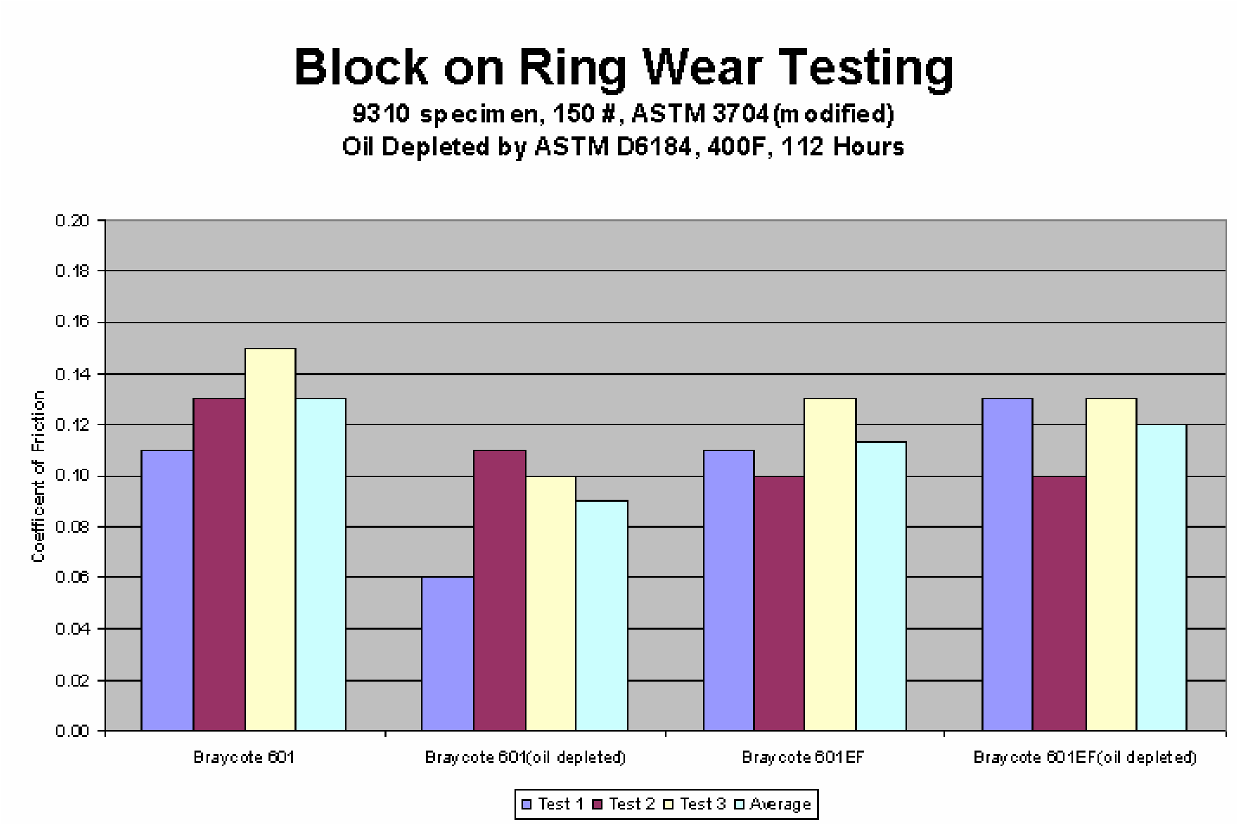

Block on Ring Wear Testing
440C specimen, 150 #, ASTM 3704(modified)
Oil Depleted by ASTM D6184, 400F, 112 Hours
Max Wear Depth (micrometers)
5.00
4.00
3.00
2.00
1.00
0.00
Braycote 600
Braycote 600(oil depleted)
Braycote 601
Braycote 601(oil depleted)
Braycote 601EF
Braycote 601EF(oil depleted)
Test1
Test 2
Test 3
Average

**Figure 6.2.1-2**



Block on Ring Wear Testing
9310 specimen, 150 #, ASTM 3704 (modified)
Oil Depleted by ASTM D6184, 400F, 112 Hours
Coefficent of Friction
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Braycote 601
Braycote 601(oil depleted)
Braycote 601EF
Braycote 601EF(oil depleted)
Test 1
Test 2
Test 3
Average


**Figure 6.2.1-3**

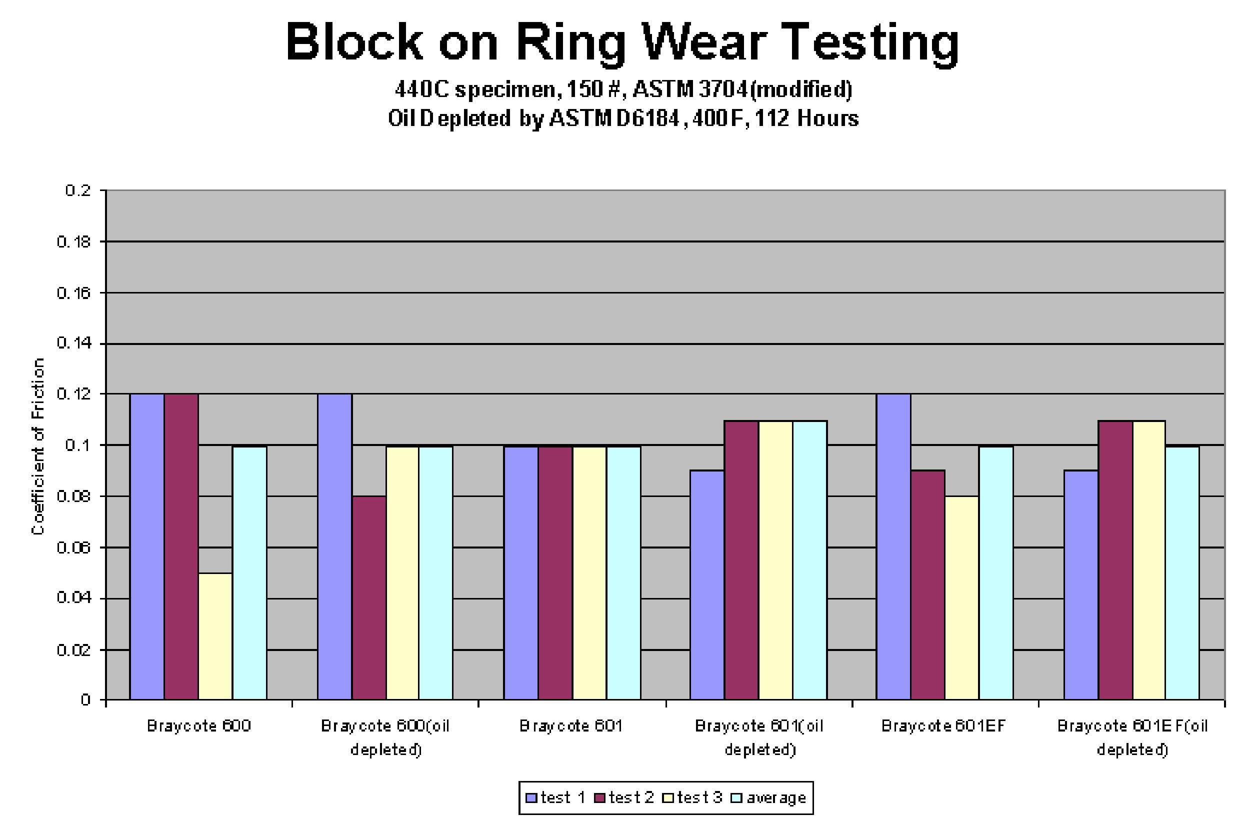

Block on Ring Wear Testing
440C specimen, 150 #, ASTM 3704(modified)
Oil Depleted by ASTM D6184, 400F, 112 Hours
Coefficient of Friction
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Braycote 600
Braycote 600(oil depleted)
Braycote 601
Braycote 601(oil depleted)
Braycote 601EF
Braycote 601EF(oil depleted)
test 1
test 2
test 3
average

**Figure 6.2.1-4**

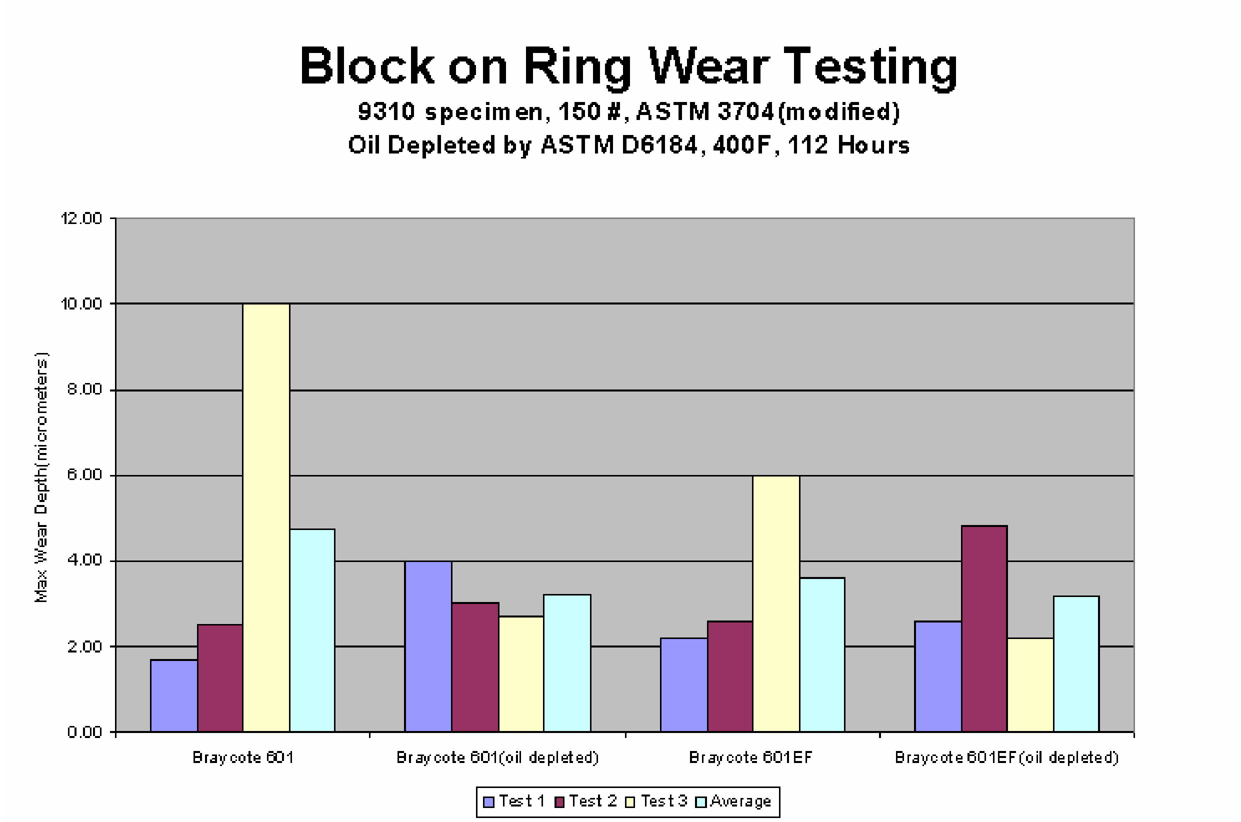



**Figure 6.2.1-5**

## CONCLUSION

For the general class of Braycote 600 greases, and absent any effects from very long-term usage (i.e., intrusion of wear particles or corrosion from long-term exposure to severe environments), there is no significant effect on lubricity resulting from separation of the grease into its oil and thickener components.

### 6.2.2 Spiral Orbit Tests

The spiral orbit tribometer (SOT) appears in Figure 6.2.2-1. First introduced by Kingsbury, the SOT is essentially a thrust bearing with flat races (plates) and a single ball. The tribometer simulates rolling, pivoting, and sliding as seen in an actual angular contact bearing. Accelerated tests are achieved by only using micrograms of lubricant on the ball. During the test, the lubricant is completely consumed, resulting in short test duration. The advantage of this type of acceleration is that operational test parameters, such as contact stress, speed, and temperature are as they will be in the final application.

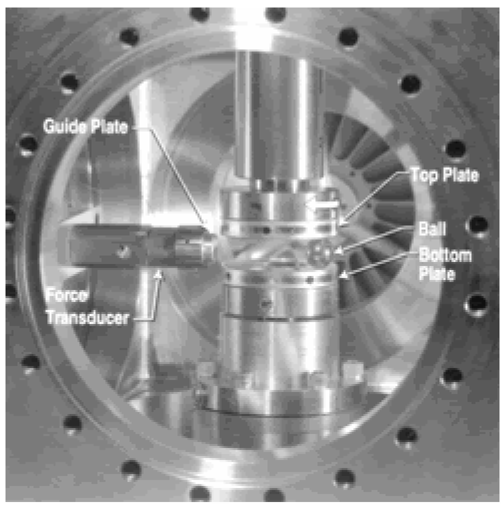



**Figure 6.2.2-1. Vacuum Spiral Orbit Tribometer (SOT)**

The tribological elements of the system appear in more detail in Figure 6.2.2-2. The lower plate is stationary while the top plate rotates at 200 rpm. The top plate rotation drives the ball in a spiral orbit. Every orbit, the ball contacts the vertical guide plate, which returns it to the original orbit radius. The straight-line region where the ball contacts the guide plate is denoted as the "scrub". The force that the ball exerts on the guide plate during the scrub is measured, from which the friction coefficient can be calculated. After leaving the scrub, the ball's spiral orbit begins again. The spiral orbit and scrub constitute a track (refer to Figure 6.2.2-2) that is stable and repeatable; it is traversed thousands of times by the ball. A detailed description of the tribometer and analysis of ball kinematics appear in Appendix A, References (Kingsbury, 1989; Jones, et al, 2000; and Pepper and Kingsbury, 2003 A/B).

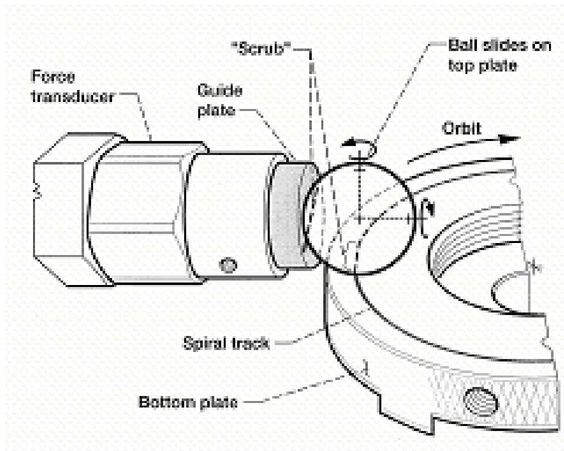



**Figure 6.2.2-2. Detailed view of the SOT Components**

### Measurement and Controls

The tribometer is operated by a computer data acquisition (DAQ) and control system developed in LabVIEW™. Analog to digital conversion is achieved using a 12-bit computer card. For vacuum tests, the DAQ automatically initiates rotation when the vacuum level reaches $1.3x10^{-6}$ Pa and terminates rotation when a preset friction coefficient is exceeded. For tests in ambient air, the is started manually.

## PROCEDURE

### Specimen Materials

The ball, guide plate, and discs were made from hardened ($R_c$~59), AISI 440C stainless steel. Before each test, the guide plate and discs were polished to an average surface roughness ($R_a$) of 0.05 microns (2 μin). The ball was grade 25 and was used as received.

### Preparation

The parts were cleaned using a levigated alumina polishing compound and rinsed with de-ionized, filtered water. The ball, discs, and guide plate were dried and placed in an ultrasonic bath of hexane for ten minutes. They were then placed into an UV-ozone box for fifteen minutes. The ball was rotated every five minutes to ensure that the entire surface had been treated. The samples were removed and the ball was lubricated.

### Lubrication

The ball was weighed dry using a microbalance. A small amount of grease was placed onto the ball and then it was placed between two plastic membranes and rotated. The ball was moved to a second set of membranes and the process repeated. The ball was then weighed. If the desired uptake of 50 µg was not achieved, the ball was placed back in between the second set of membranes and rotated again. This process was repeated until the desired amount of lubricant was obtained.

### Test Setup

After the samples were cleaned, the guide plate and discs were installed in the tribometer, and the ball was inserted so that it was touching the guide plate. This was accomplished to ensure that the ball was always at the same track diameter and there was no ‘run-in’ time, or revolutions, that the ball did not strike the guide plate. The load was applied and the test was started.

### Testing

All tests were performed in ambient air using a mean Hertzian stress of 1.5 GPa and a top disc rotational speed of 200 rpm. The DAQ constantly monitored guide plate force, load, revolutions, and contact resistance. The test was terminated when a coefficient of friction of 0.28 was exceeded.

### RESULTS

The results of the SOT testing are summarized in Table 6.2.2-1 and in Figure 6.2.2-3.

**Table 6.2.2-1. Shuttle Rudder Actuator Grease Test Matrix**

**SOT Testing**

| | Tests | Total Tests |
|---|---|---|
| Braycote 601EF | x2 | 2 |
| Braycote 601 (KC17) | x2 | 4 |
| Braycote separated grease (03-03) | x2 | 6 |
| Hamilton Sunstrand Grease Code A14 | x2 | 8 |
| Hamilton Sunstrand Grease Code A27 | x2 | 10 |
| SunGear Grease (D9M015) (S12) | x2 | 12 |
| Engineering Test Unit Grease Code E20 | x2 | 14 |
| Engineering Test Unit Grease Code E21 | x2 | 16 |

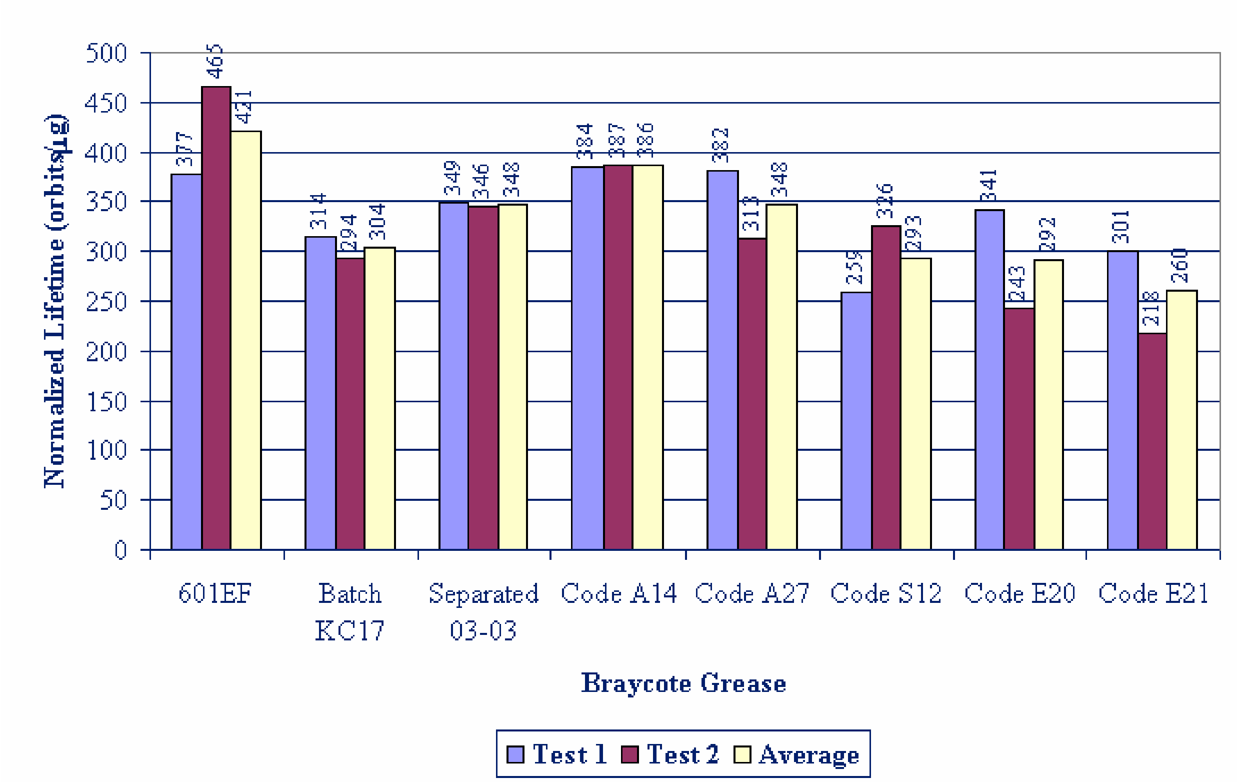



**Figure 6.2.2-3. Shuttle Rudder Actuator Grease Test Matrix**

With the exception of the samples designated "601EF", all of the grease was Braycote 601. The samples designated "Engineering Test Unit" (E Codes) were removed from that unit, which has not experienced flight environments. The remaining samples (A Codes) were all removed from OV-103. The sample designated "KC17" was remixed manually prior to testing, while the remaining samples were tested as received.

## CONCLUSION

The variations between sample groups are well within the scatter band that is typical of SOT testing. Taking the sample designated "KC17" as the standard, there is no observable effect on lubricity due to separation of the grease components. Comparison of the samples from the engineering test unit indicates there is no detrimental effect on lubricity from the flight environment.

### 6.2.3 WAM Tests

**PROCEDURE**

Polishing wear tests were conducted on samples of aged Braycote 601 with and without artificial removal of base oil. Per ASTM D6184-98, thermal evaporation was used to remove approximately 3% of the polyperfluoropolyalkyether (PFPE) base oil from the grease. A ball-on-disc WAM test machine shown in Figure 6.2.3-1 was used to evaluate the polishing wear performance of Braycote 601 (batch KC17).

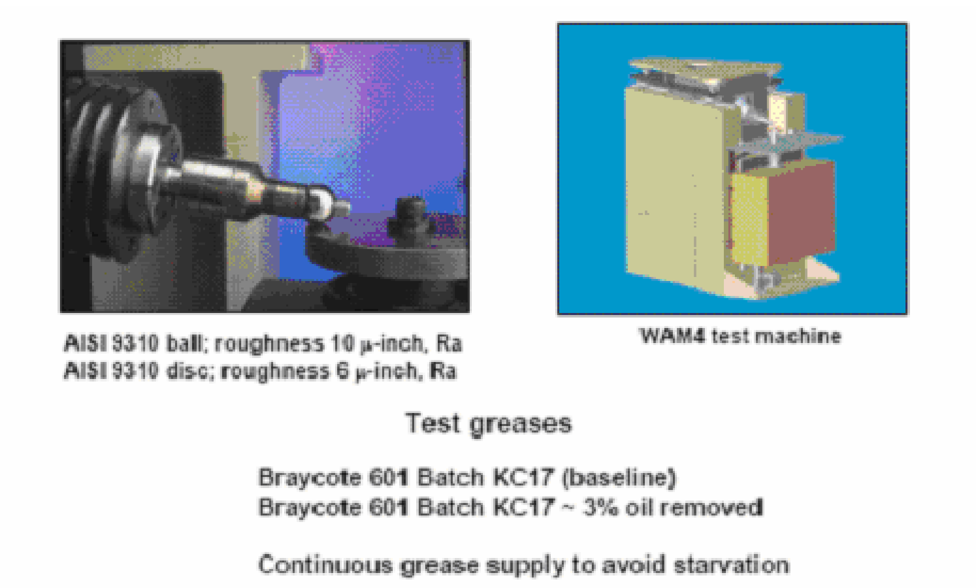



**Figure 6.2.3-1. WAM Test Machine and Configuration for Polishing Wear Test with Braycote Grease**

The WAM test machine provides computer-controlled loads and motions between test specimens to produce various types of gear failure modes. With detailed information on tooth profile, loads and motions, simulation of gear service conditions can be made (refer to Figure 6.2.3-2).

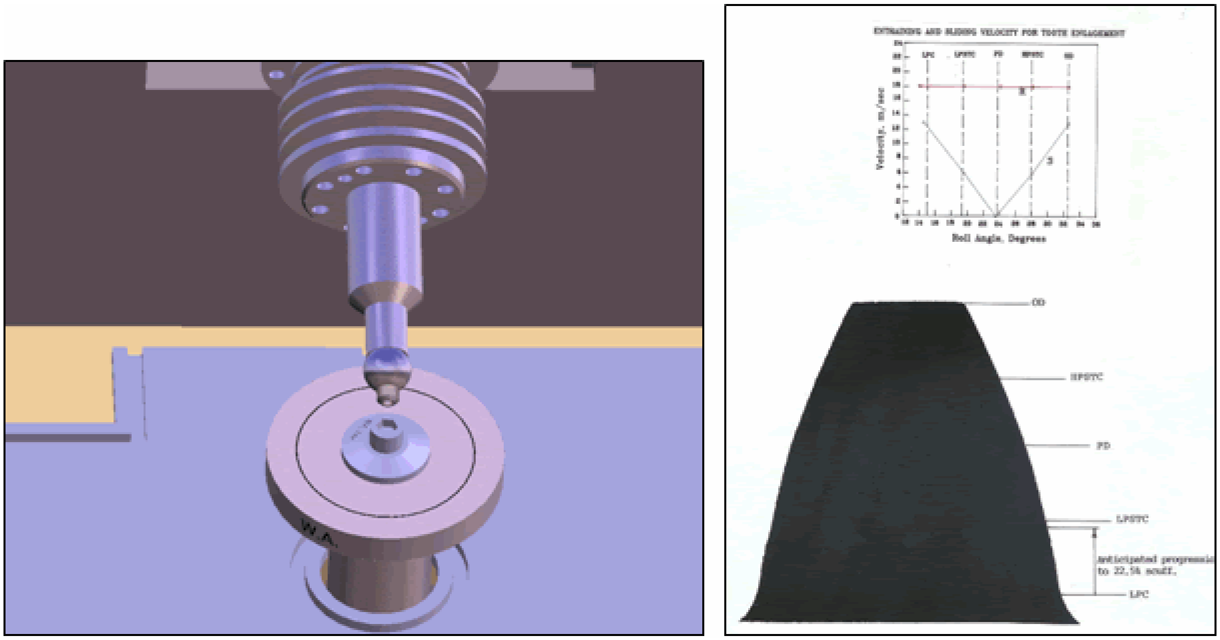



**Figure 6.2.3-2. Simulation of Gear Tooth Contact Conditions**

Rolling/sliding velocities and contact stresses at planetary contact not known at time of testing

Without immediate knowledge of R/SB gear contact conditions, test parameters were selected to cause polishing wear under accelerated conditions. The selected test parameters are provided below:

| | | | |
|---|---|---|---|
| Entraining (rolling) velocity: | 50 in/s | 50 in/s | 25 in/sec |
| Sliding velocity: | 2.51 in/s | 20 in/s | 40 in/sec |
| Contact stress (load) | exponential rise in load (stress: 106 to 356 ksi) | | |
| Temperature: | Ambient; temp rise due to friction ~ 80C (176 F) | | |

To achieve a range of accelerated conditions, the ball and disc velocity vectors were placed at various angular positions, as shown in Figure 6.2.3-3. The test grease, which was initially applied to the surfaces, was manually moved back into the running track to avoid starvation.

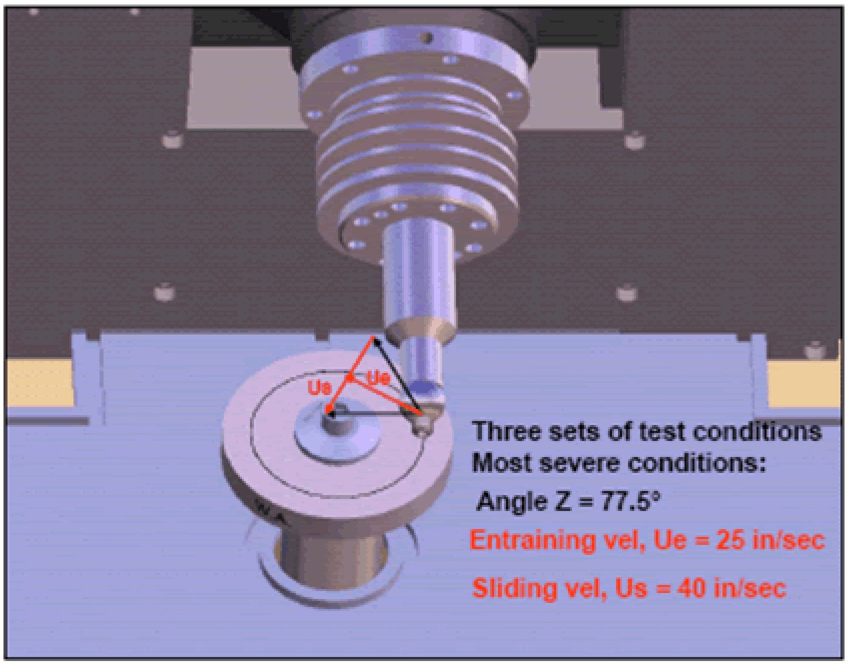



**Figure 6.2.3-3. Velocity Vector for Polishing Wear Tests with Braycote 601**

The test specimens were fabricated from AISI 9310 steel and heat-treated to HRC 63. Surface finish and heat treatment were carefully controlled to assure repeatability. The operating conditions were selected to achieve an elastohydrodynamic film thickness less than the combined roughness features on the test specimens. These conditions caused the surface roughness features to interact so that the grease lubricating properties could be evaluated in terms of polishing wear.

## RESULTS

A typical test plot of traction (friction) coefficient over a test period of 30 minutes is shown in Figure 6.2.3-4. The polishing wear areas on the test specimens shown in this figure are similar to the polishing wear seen on R/SB actuator planetary gears (i.e., without fretting damage).

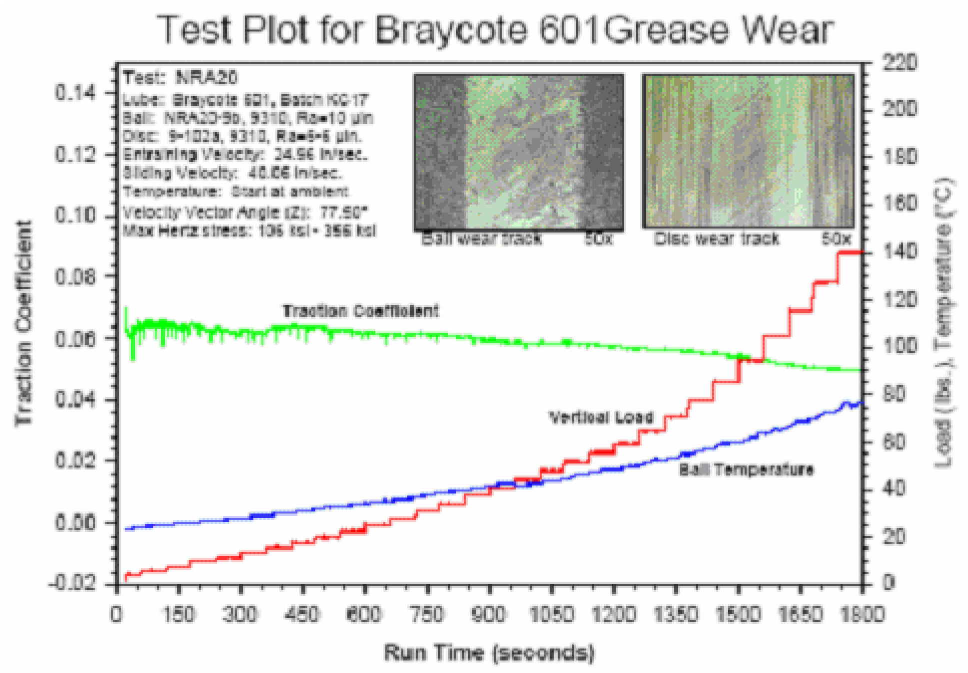



**Figure 6.2.3-4. Test Plot from Polishing Wear Test with Braycote 601**

The polishing wear results of Braycote 601 with and without oil removed are shown in Figure 6.2.3-5. Three sets of test are shown, each corresponding to a set of entraining and sliding velocities.

## CONCLUSION

The results show no noticeable difference in wear performance due to the loss of 3% oil.

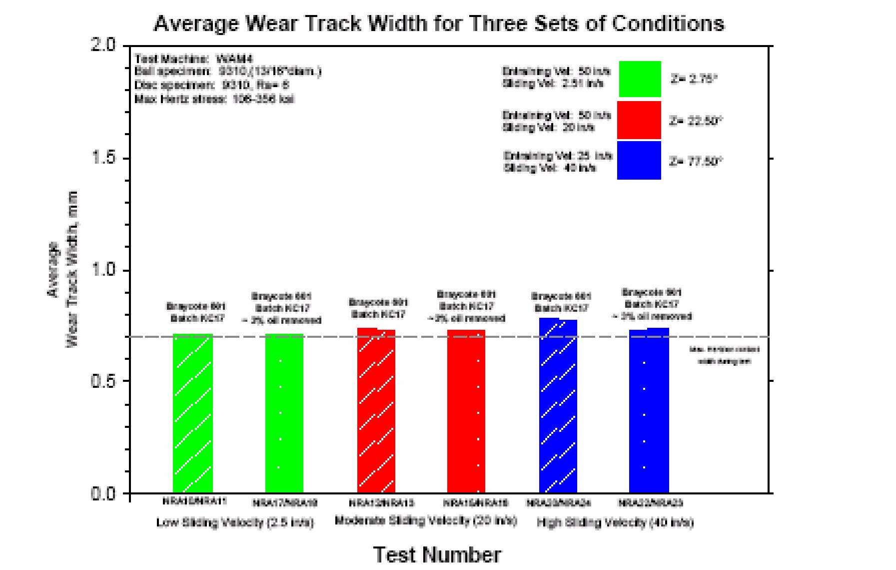



**Figure 6.2.3-5. Polishing Wear Test Results with Braycote 601**

## 6.3 TESTS TO ADDRESS CORROSION DURING STORAGE

### 6.3.1 WAM Testing to Understand the Mechanism of the Observed Pitting/ Corrosion

Based on the damage patterns observed on the OV-103 gears, and reinforced by the Literature Review, it was postulated that the most serious wear mode on the R/SB planetary gears is fretting damage caused by dither motion or oscillating loads. In its most severe form, fretting wear can be accompanied by fretting fatigue cracks and spalling, as shown in Figure 5.0-1. This occurs while the R/SB actuators are being used in an active control mode to hold the rudder panels in a set stationary position. Examples include ground processing (when the panels may be held in the same position for months at a time); ferry transport; ground transport on the mobile launching pad; and pre-flight time at the launch site.

The dither motion expected during the conditions described above was simulated using a new WAM fretting test machine, shown in Figure 6.3.1-1. The machine provided two test stations, which are operated simultaneously. The WAM fretting test machine is designed to produce fretting motions with amplitudes in the range of 0.001-0.004 inches. The test machine can also provide low frequency translation motion on the order of 0.2 inch. Translation motions are used to replicate normal gear operation and run-in without fretting motions. The fretting test machine was modified to accommodate AISI 9310 test specimens. A ball on flat configuration was used so that high Hertzian contact stresses could be achieved within the load limit of the machine.

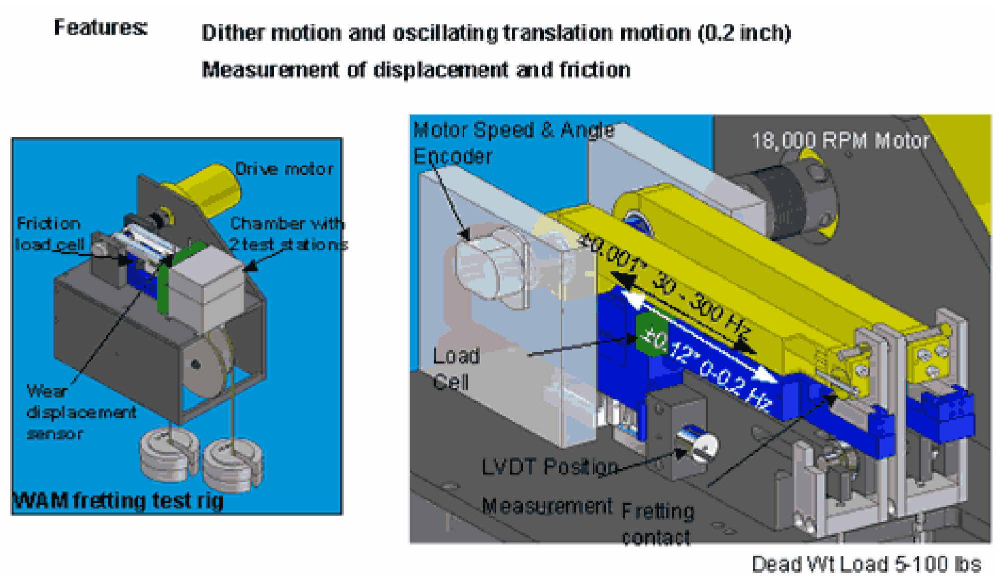
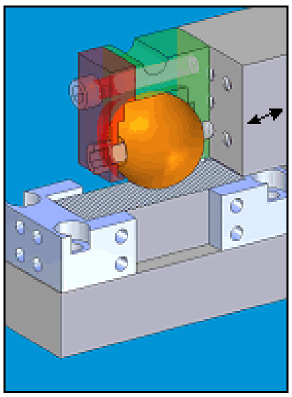



**Figure 6.3.1-1. WAM Fretting Test Machine**

The most severe fretting damage occurred when the magnitude of dither motions was less than the dimensions of the elastic deformation area of the contact. This resulted in cycles of surface strain and micro-slip with no opportunity for lubricant replenishment. A portion of the contact is not exposed. Typical measurements of surface displacement and friction are shown in Figure 6.3.1-2. An open friction vs. displacement curve reflects partial elastic strain and partial frictional slip. Slip tends to occur at the outer edges of the contact where the Hertzian stress is low. The amount of elastic strain (and perhaps plastic flow) that is built up during dither motion is a function of the friction coefficient. In this case the friction coefficient is 0.48. A well-lubricated contact would have a friction coefficient on the order of 0.12 (boundary lubrication).



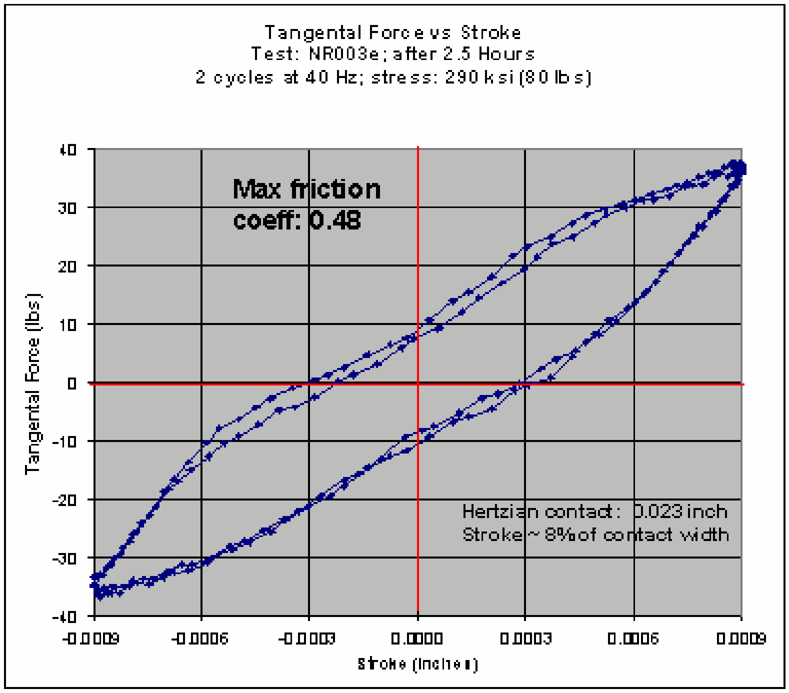



**Figure 6.3.1-2. Displacement and Friction Force During Fretting Wear Test**

Surface deterioration with fretting was shown to proceed along a wear mode and/or a fatigue mode. Examples of fretting wear and fretting fatigue produced by this technique are shown in Figures 6.3.1-3 and 6.3.1-4. These features bear a strong superficial resemblance to those observed on the R/SB gears, taking into account the configurational differences between the flight hardware and the test specimens.

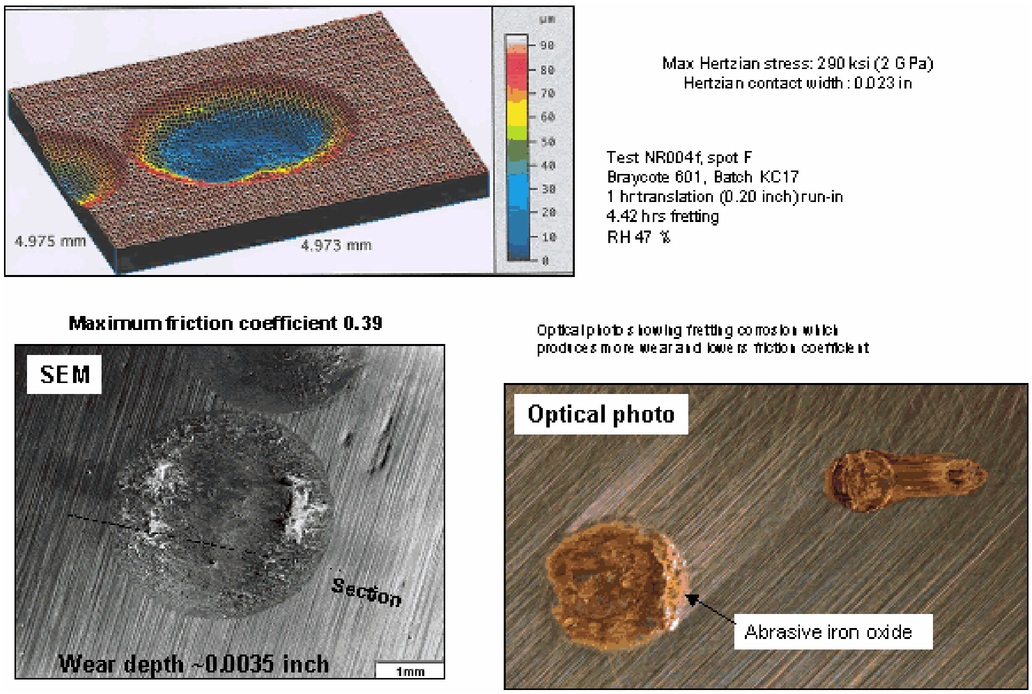



**Figure 6.3.1-3. Examples of Fretting Wear**

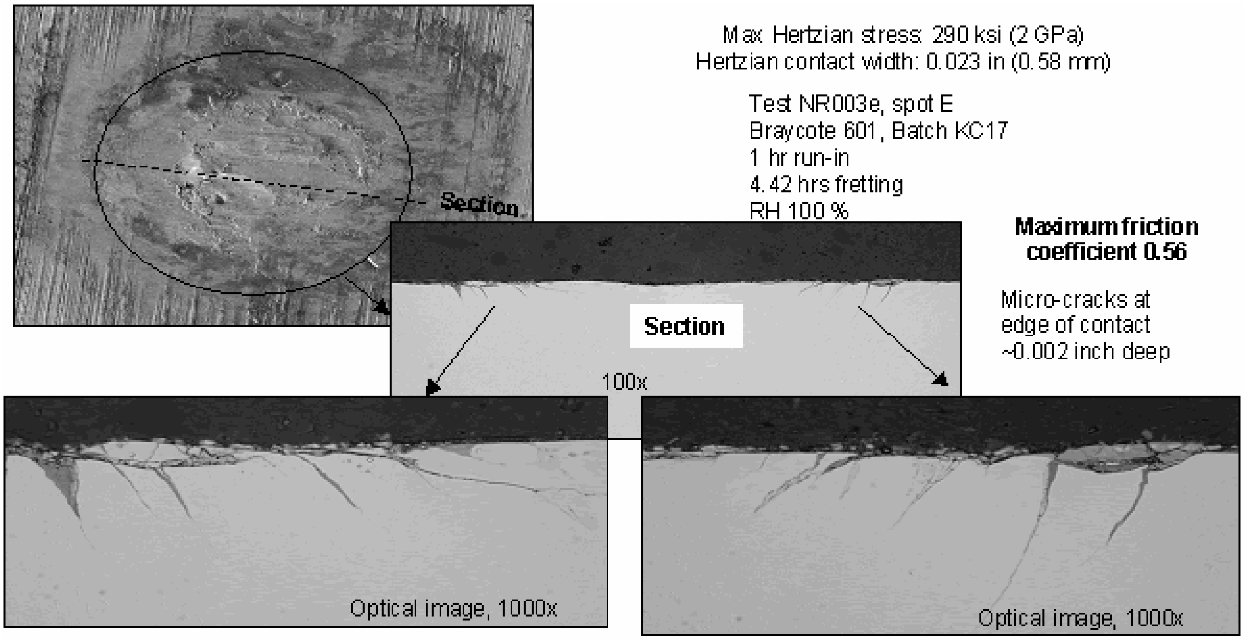



**Figure 6.3.1-4. Example of Fretting Fatigue (100% humidity)**

### CONCLUSION

Although not conclusive, this test series reinforced the postulate that the pitting/corrosion conditions observed in the OV-103 R/SB actuators was tribologically induced, and thus was unlikely to exist in the actuators that had been removed from storage.

## 6.3.2 Isothermal Gravimetric Analysis of Braycote 601 on Carburized 9310 Steel

### Background

Since degradation of PFPE grease has been accepted as a potential problem in the R/SB mechanism, testing designed to address this concern was justified. The basic intent of this work was to evaluate the thermal stability of Braycote 601 grease on carburized 9310-steel. TGA was used to perform isothermal experiments on 9310 coated with Braycote 601 grease. Mass loss was measured at three different temperatures versus time between 385-410 min. The average rate constant associated with the temperature of interest was then determined. The average rate constants obtained at different temperatures were used to obtain the associated energy of activation, $E_a$. The percentage mass remaining after a specified period of time, and the time associated with a specified percentage of mass loss, were calculated at various temperatures.

## PROCEDURE

Experiments designed to address the thermal stability of Braycote 601 grease on carburized 9310 steel were performed by TGA, and temperature dependant average rate constants associated with the mass loss of Braycote 601 were determined. Arhenius treatment of the average rate constants, derived from the isothermal TGA analysis, afforded the activation energy associated with mass loss and allowed for further calculation of rate constants at temperatures relevant to the R/SB actuators. Calculations quantifying the thermal stability of Braycote 601 on carburized 9310 were performed and evaluated according to the storage and service environments witnessed by the R/SB actuator.

### First Order Treatment of TGA Data Obtained From Isothermal TGA

Consider a given mass of grease, $\mathbf{m_o}$, losing mass over a time interval, t, producing $\mathbf{m_t}$. This process should exhibit first order behavior similar to outgassing from grease and can be represented by Equation (1) describing the change in mass of grease with respect to time, where **k** is a temperature dependent rate constant.

**EQ (1)** $-dm/dt = km$

**EQ (2)** $-dm/m=k(dt)$

Integration of Equation (2) followed by taking the exponential of both sides yields Equations (3) and (4), respectively.

**EQ (3)** $\ln(m_t/m_o) = -kt$

**EQ (4)** $(m_t/m_o)=\exp(-kt)$

For convenience, let the term $\mathbf{q=m_o-m_t}$ represent mass loss. Substituting for $\mathbf{m_t}$ into Equation (4) yields Equation (5).

**EQ (5)** $(1-q/m_o)=\exp(-kt)$

The term $\mathbf{q/m_o}$ is the mass loss ratio and $\mathbf{w=100q/m_o}$ the percent mass loss. After multiplying each side of Equation (5) by 100 and substituting **w** for $\mathbf{100q/m_o}$ we obtain Equation (6). Taking the natural logarithm of each side of Equation (6) and rearranging yields Equation (7) in a form convenient for TGA analysis.

**EQ (6)** $(100-w)=100\exp(-kt)$

**EQ (7)** $\ln(100-w)=\ln 100-kt$

The term **(100-w)** is by definition the % mass remaining and is conveniently displayed on the y-axis of an isothermal TGA plot versus time. Plots derived from isothermal TGA data of **ln(100-w)** versus **t** should yield linear plots (first order behavior) with slopes affording $k_n$ for a given temperature, $T_n$. Nonlinear results would be indicative of non-first order behavior. A similar derivation for second order behavior could be employed if necessary, but higher order behavior would require regression analysis to provide an adequate best fit for the data. Rate constants obtained at several temperatures by isothermal TGA experiments can then be treated according to the Arhenius equation, Equation (8), where **k** is the rate constant obtained by TGA as described above, **A** is a pre-exponential factor, $E_a$ is the activation energy, **R** is 1.986 cal/(Kelvin mole), and **T** is absolute temperature. A plot of **ln(k)** versus **1/T** according to Equation (8) should be linear and allows for the $E_a$ to be determined from the slope of the plot.

**EQ (8)** $\ln(k)=\ln A-(E_a/RT)$

Once the activation energy, $E_a$, is determined, calculation of rate constants and their corresponding rates of mass loss at any temperature can then be obtained by utilization of Equations (8) and (7), respectively.

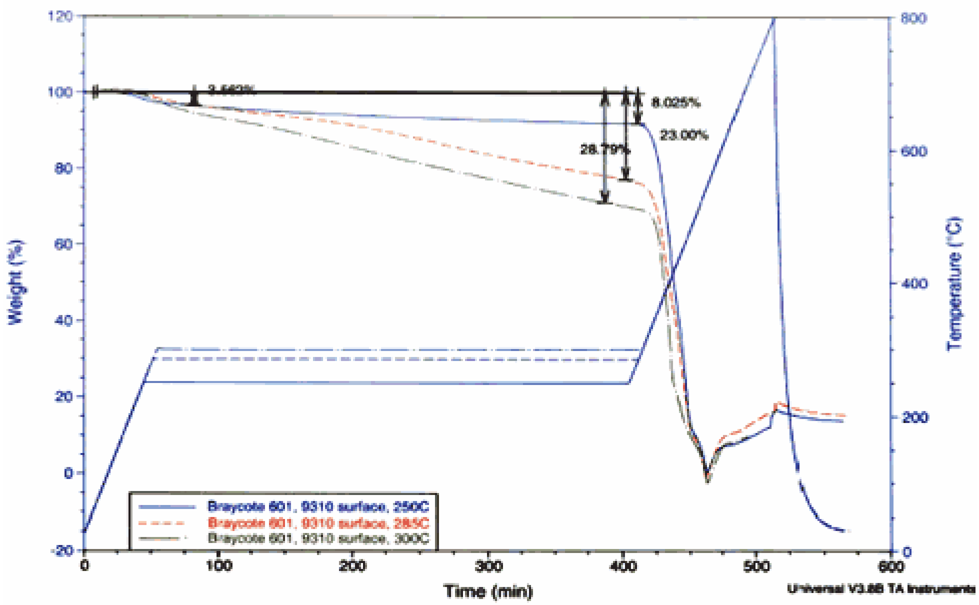



**Figure 6.2.4-1. Isothermal Analysis of Braycote 601 on Carburized 9310 Steel**

## RESULTS

Isothermal experiments conducted by TGA (NASA JSC, Devivar, Sullivan, Jacobs) produced the thermograms shown in Figure 6.2.4-1. Treatment of the data as described earlier allowed for the generation of temperature dependent rate constant data. Due to the limited data available, and the possibility of more than one mechanism operating under the conditions of the experiments performed, average rate constants were calculated according to Equation (9). This equation was derived for the net mass loss beginning at t=0 and w=0 and proceeding to some time t>0 where w was determined. This approach had the advantage of examining the net change as opposed to treating the data as a series of independent steps that were not fully understood. This approach was undertaken due to the appearance of shoulders present early in the isothermal portion of the runs, and initial increases in mass observed during the ramping phase used to attain the desired isothermal conditions. These phenomena suggest multistep processes occurring during the ramping and isothermal run. Results are presented in Table 6.2.4-1.

**Table 6.2.4-1. Average Rate Constants Obtained From Isothermal TGA Analysis**

| mass loss | time | $k_{ave}$ ($min^{-1}$) | T (K) | 1/T ($K^{-1}$) | ln($k_{ave}$) |
|---|---|---|---|---|---|
| 8.03 % | 365 min | 2.29 e-4 | 523 | 1.91 e-3 | -8.382 |
| 23.00 % | 349 min | 7.49 e-4 | 558 | 1.79 e-3 | -7.197 |
| 28.79 % | 331 min | 1.03 e-3 | 573 | 1.75 e-3 | -6.878 |

**EQ (9)** $k_{ave} = [\ln(100) - \ln(100-w)]/t$ where w = % mass loss above

A plot of $k_{ave}$ vs 1/T according to Equation (8) was generated and is shown in Figure 6.2.4-2. The activation energy was obtained from the slope and is displayed in Table 6.2.4-2.

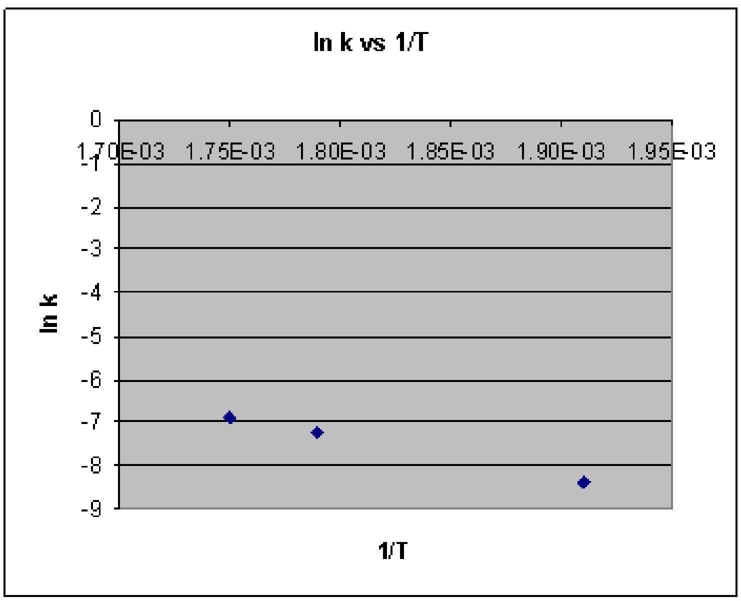



**Figure 6.4.2-2. Plot of ln k versus 1/T ($K^{-1}$)**

**Table 6.4.2-2. $E_a$ and lnA (determined from Figure 6.4.2-2)**

| $E_a$ (kcal/mole) | lnA | $R^2$ |
|---|---|---|
| 18.89 | 9.79 | 0.998 |

Consider the 298K condition and the activation energy derived from Figure 6.4.2-2. Using Equation (8) to obtain the calculated rate constant of k=2.41 e-10 min-1 at 298K and t=17 years

(8.94 e6 min), percentage mass remaining of 99.78 % was calculated according to Equation (7) corresponding to a calculated mass loss of 0.22% or 2200 ppm, supporting the conclusion that Braycote 601 grease was stable under conditions of storage on 9310 carburized steel. Times associated with one percent mass loss at different temperatures were calculated and are shown in Table 6.4.2-3.

**Table 6.4.2-3. Times Calculated For One Percent Mass Loss as a Function of Temperature**

| T (K) | $E_a$ (cal/mole) | t (years) 1% mass loss |
|---|---|---|
| 298 | 18.9 e3 | 7.93 e1 |
| 313 | | 1.72 e1 |
| 373 | | 1.29 e-1 |

### CONCLUSION

Corrosion during controlled storage at ambient temperature is not predicted by thermodynamic analysis and testing.

### REMARKS

The data presented were based on the activation energy obtained from the average rate constant data assuming a pseudo first order mass loss. The time interval of the isothermal period was corrected for the ramping phase, and the entire mass loss, including mass lost during the ramping period, was attributed to the isothermal condition. This assumption was worst case and had the effect of increasing the value of k by assuming a higher mass loss over a shorter time interval for a given isothermal condition.

# 7.0 Findings, Observations, and Recommendations

## Findings

Pursuant to the two issues that led to this assessment, stated in Section 5.0, and based on the testing described in this report, the findings of the NESC are as follows:

Issue 1. There is no significant effect on the lubricity of Braycote 601 grease due to separation into its component oil and thickener, or due to any other phenomenon that might occur during controlled storage for 17 years.

Issue 2. Under the conditions of controlled storage, there is no possibility of pitting/ corrosion and cracking within the R/SB mechanisms resulting from chemical reactions involving the separated grease and the gear housing material, 9310 steel.

### Observations

The stated margins of safety against structural failure of a gear tooth are low, and it is possible that non-conservative assumptions regarding load sharing within and between gears have been made in the structural analysis.

The existence of the corrosion and pitting observed in the OV-103 hardware had not been accounted for in the analysis, indicating a possible fatigue and/or fracture mechanics issue.

The effects of grease degradation in a bearing environment (e.g. simulating roller and ball bearing loads) have not been addressed.

### Recommendations

1. The R/SB actuators from OV-103 do not require disassembly inspection to address either of the two issues introduced in Section 5.0.

2. The Program should initiate a Delta Certification program to address the following issues:

   - Potential negative margins of safety resulting from nonconservative assumptions regarding load sharing within and between gears.
   - The existence of corrosion and pitting in the gear teeth, as observed in OV-103. This should include gaining a root cause understanding of the origin and progression of corrosion pits and cracks.
   - The effects of lubricant aging on the performance of the sun gear support bearings.
   - The life limit of the spare actuators.
   - The effect of material variables, such as surface finish, depth of carburized layer, temperature, etc.

## 8.0 Lessons Learned

1. The data contained in this report constitute lessons learned that are specific to the issues to which this report is responsive.

2. The following lesson learned is of general interest and has been formally entered into the NASA Lessons Learned Information System (LLIS).

> "Programs should periodically review hardware components to ensure that they are operating within qualification and certification limits. Where hardware exceeds these limits, testing or analysis should be performed to properly envelop the actual operational environment."

# 9.0 List of Acronyms

| | |
|---|---|
| AISI | American Iron and Steel Institute |
| ASTM | American Society for Testing and Materials |
| BF | Body Flap |
| C | Celsius |
| F | Fahrenheit |
| Foot/Minute | Ft/Min |
| DAQ | Data Acquisition |
| FTIR | Fourier Transform Infrared Spectroscopy |
| Gpa | Gigapascal |
| GRC | Glenn Research Center |
| GSFC | Goddard Space Flight Center |
| HPLC/GPC | High Performance Liquid Chromatography/Gel Permeation Chromatography |
| HRC | Rockwell C Hardness (metallurgy) |
| HS | Hamilton Sundstrand |
| Lbs | Pounds |
| ITA/I | Independent Technical Assessment/Inspections |
| JSC | Johnson Space Center |
| KSC | Kennedy Space Center |
| LaRC | Langley Research Center |
| LLIS | NASA Lessons Learned Information System |
| Mm | Millimeter |
| MSFC | Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| NDE | NESC Discipline Expert |
| NESC | NASA Engineering and Safety Center |
| NRB | National Review Board |
| OV-103 | Orbital Vehicle |
| PCTFE | Polychlorotrifluoroethylene |
| PFPE | Polyperfluoropolyalkyether |
| POC | Point-of-Contact |
| PRT | Problem Resolution Team |
| PTFE | Polytetrafuloroethylene polymer |
| R/SB | Rudder/Speed Brake |
| SCF | Super Critical $CO_2$ Chromatography |
| SEC | Size Exclusion Chromatography |
| SOT | Spiral Orbit Tribometer |
| SPRT | Super Problem Resolution Team |
| TGA | Thermal Gravimetric Analysis |
| UV | Ultraviolet |
| WAM | Wedeven Associates Machine |
| XPS | X-ray Photoelectron Spectroscopy |

# Volume II: Appendices

# APPENDIX A. REFERENCES

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# APPENDIX B. ASTM D6184-98

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# APPENDIX C. ASTM D 3704-96

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# Plan Approval and Document Revision History

Approved: Original signature on file. 5/26/04

NESC Director Date

| Version | Description of Revision | Author | Effective Date |
|---|---|---|---|
| 0.01 | Draft | P. Munafo, Lead | |
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