# Space Shuttle Body Flap Actuator Bearing Testing for NASA Return to Flight

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## Abstract

The Space Shuttle body flap (BF) is located beneath the main engine nozzles and is required for proper aerodynamic control during orbital descent. The body flap is controlled by four actuators connected by a common shaft and driven by the hydraulic power drive unit. Inspection of the actuators during refurbishment revealed three shaft bearings with unexpected damage. One was coated with black oxide on the balls and race wear surfaces, a second contained a relatively deep wear scar, and the third with scratches and an aluminum particle in the wear track. A shaft bearing life test program was initiated to measure the wear life and explain the 5.08-micrometer wear scar. A tribological analysis was conducted to demonstrate that the black oxide coated wear surfaces did not damage the bearing, interfere with the lubrication, or cause severe bearing wear. Pre-damaged (equivalent of 30 missions), commercial equivalent bearings and previously flown shaft bearings were tested at axial loads, speeds, and temperatures seen during flight operations. These bearing were successfully life tested at 60°C for 24 hours or 90 flights. With a safety factor of 4X, the bearings were qualified for 22 flights when only a maximum of 12 flights are expected. Additional testing at 23°C was performed to determine the lubricant life and to further understand the mechanism that caused the blackened balls. Test results indicating bearing life was shortened at a lower temperature surprised the investigators. Start\Stop bearing testing that closely simulates mission profile was conducted at 23°C. Results of this testing showed lubricant life of 12 flights including a safety factor of four. Additional testing with bearings that have the equivalent of 30 missions of damage is being tested at 23°C. These tests are being performed over the Shuttle load profile to demonstrate the residual bearing life in the actuators exceeds 12 missions. Testing showed that the end of the shaft bearing life was characterized by bearing temperature rise, preload drop, and the onset of a severe wear bearing failure mechanism. The severe wear failure mechanism is characterized by rough wear scars, extensive bearing wear and steel transfer between the balls and the races.

## Introduction

The BF is part of the Space Shuttle Orbiter control system that operates primarily during the critical descent maneuvers. The Shuttle body flap is supported and controlled by four body flap actuators (BFA) sharing a common, segmented drive shaft. The common shaft is driven by the hydraulic power distribution unit. During inspection of these actuators, one of the input shaft bearings was discovered to have blackened balls and a blackened wear track in the race after the actuator had completed approximately 20 missions [1, 2]. It was deemed unacceptable for service, replaced and the used grease was discarded. Visual examinations of most of the BF actuators in the fleet revealed no evidence of blacken balls or race wear tracks in the shaft bearings. The used shaft bearings were cleaned, inspected, re-lubricated and reinstalled in the actuators or scrapped. Subsequent microscopic inspection and metrology of these shaft bearings revealed significant wear and possible plastic deformation in a second shaft bearing [3]. A third shaft bearing was found to have scratches and an aluminum particle in the wear track. To determine if actuators with used bearings were acceptable to re-fly for twelve missions, a bearing test program was initiated at the Marshall Space Flight Center.

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## Body Flap Actuator Background

The Body Flap actuator is shown in Figure 1. Several failure modes can end the life of the BF actuator bearings. Fatigue spalling, fretting fatigue, lubricant failure, high temperature oxidation, corrosion pitting, severe wear or combinations of these mechanisms can cause bearing failure. Corrosion pits or wear damage accelerate fatigue crack growth that can cause fatigue failure before the bearing reaches the B1 or B10 fatigue life. If the bearing wear life or the Braycote 601 grease life is exceeded, the bearings can fail. However, because the actuators possess very high driving torques, the worst bearing failure mode was expected to be a broken ball or bearing race that could jam the actuator as well as the common drive shaft and cause an actuator performance failure.

The design criteria for the space shuttle (OV) BFA are 100 missions and 10 years. During the 1990s, excessive BF flutter during launch and excessive BF housing corrosion led to disassembly and inspection of BF actuators. In October 2002, bearings from the S/N 402 and S/N 405 actuators were cleaned and microscopically inspected to find out if ball bearings in the BFA assemblies needed to be replaced. As part of that investigation, shaft bearing P/N 5902050, S/N V6L009, from body flap actuator S/N 402, was found to possess unusually dark wear surfaces when compared to the rest of the bearings under examination (Figure 2) [1, 2]. NASA's Engineering and Safety Center (NESC) became aware of this issue and initiate an Independent Technical Assessment to assess this bearing and all other bearings in the Shuttle's Rudder Brake and Body Flap Actuators [4].

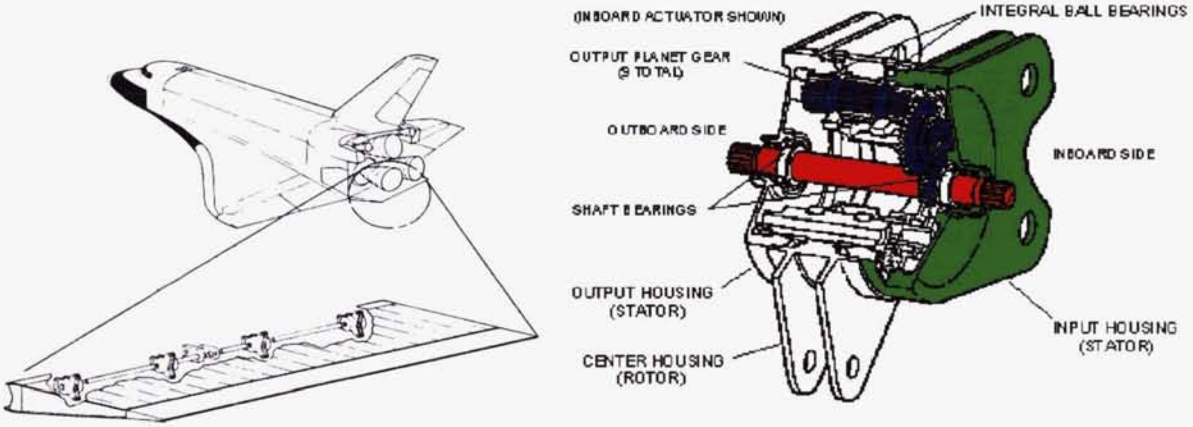

**Figure 1. Space Shuttle Body Flap Actuator**

**Figure 2. Body Flap Shaft Bearing S\N V6L009**

### Analysis of BFA Bearing with Black Balls

Visual inspection of P/N 5902050, S/N V6L009, revealed a black, tribological coating on the balls and race wear tracks (Figure 3). It should be noted that no other bearing in the Body Flap or Rudder/Speed Brake actuators was found to contain the black, tribological coating on the wear surfaces. Minor corrosion was noted on the inner and outer raceways. The grease present in the bearing was brown in appearance due to the tribological decomposition of the Braycote 601 grease and iron oxide wear debris. The recommendation based on microscopic examination analysis was to replace the bearing since the wear surfaces were black and it suffered Brinell damage during disassembly.

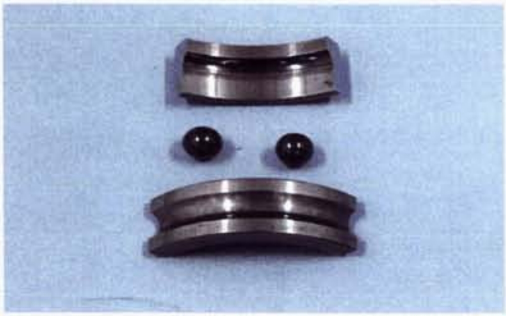

**Figure 3. Black bearing after sectioning and cleaning**
Note black balls and the dark bands present on the raceways.

Further work performed in 2004 by Hamilton Sundstrand, Inc. reported that the inner ring contained a black tribological coated band. The black band or wear track possessed a smooth matte finish with a grain boundary like structure. Outside the black wear track, the original surface was still evident along with the original finish marks. The outer ring contained a similar black coated wear band (Figure 4). The wear surface of the outer race was similar in appearance to the wear surfaces present on the balls.

**Figure 4. Magnified views of the black wear tracks in the inner race (left) and outer race (right) are shown. Note the false brinelling marks. The dark brown color is an optical aberration of the black color.**

Scanning Electron Microscopy (SEM)
Scanning electron microscopy was performed on segments of the black ball bearing by various groups [5]. The segments examined included the balls, inner raceway and outer raceway. Analysis of the balls by energy dispersive spectroscopy (EDS) revealed that the black tribological coating was composed of carbon and iron oxide. The coating was porous and appeared to be uniform over the entire ball surface. A few skid marks were noted (Figure 5). In addition, each ball possessed a moon-shaped spot that appeared to have penetrated the burnished coating. The spot was probable caused by a drop of rain

water absorbing corrosive chemical from the degraded grease and dissolving the black coating during Shuttle storage.

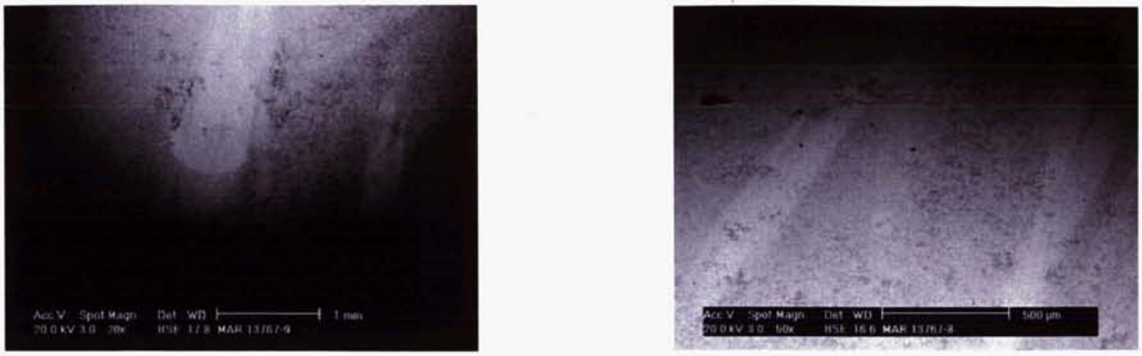

**Figure 5. Scanning electron micrograph of black ball showing spot (left) and skid marks (right)**

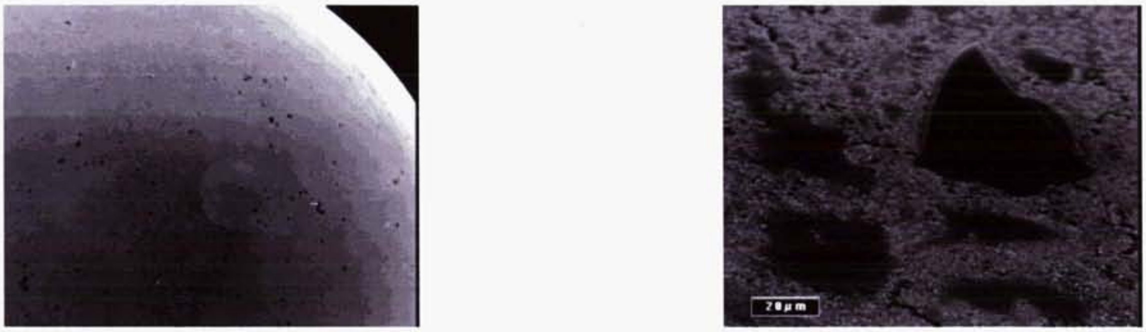

**Figure 6. Scanning electron micrographs of the black ball (left) and magnification of particle present on the ball surface (right)**

Higher magnification of the ball revealed some particles present on the ball (Figure 6). The presence of aluminum and silicon, in addition to other elements detected by EDS on these particles, were likely attributed to the bentonite clay additive present in the Braycote 601 grease and not contamination as was originally proposed. Analysis of the inner and outer raceways showed surfaces similar to the black ball. EDS performed on those surfaces detected the carbon iron oxide coating found on the black balls. Examination of the inner raceway away from the burnished band showed the original finishing marks which gradually translated into a smoother region as the burnished area was approached (Figure 7). Figure 8 shows the surface for the coating present on the black ball obtained by surface profilometry.

**Figure 7. Scanning electron micrograph of the outer raceway in the region above the burnished band (left), and within the burnished band (right)**

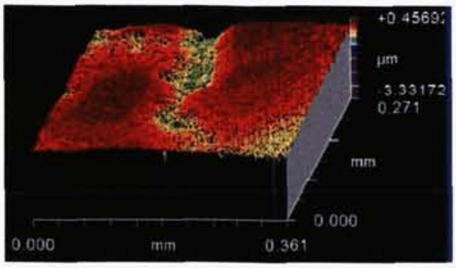

**Figure 8. Surface profilometry trace showing the coating present on the black ball including a segment of the grain boundary-like structure in the center**

Raman Spectroscopy

Raman spectroscopy of the black balls showed carbonaceous peaks from the carbon coating on the surface of the complex iron oxide, black, tribological coating [6]. Specifically, the diamond, D, and graphitic, G, peaks were observed confirming the presence of amorphous carbon (Figure 9).

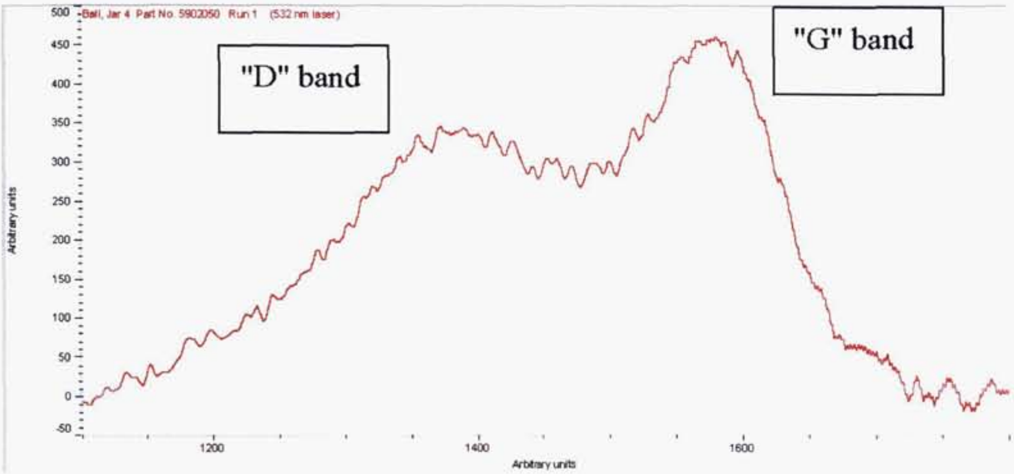

**Figure 9. Raman spectrum for black ball showing the graphitic (G) and diamond (D) peaks associated with amorphous carbon.**

X-ray Photoelectron Spectroscopy (XPS)

XPS was performed on the black ball at three different locations and on the inner race. Following the initial scans, depth profiling was performed by application of fifteen sputtering cycles, each lasting ten seconds, and a total sputter time of 450 seconds per location. The results show a carbon-rich coating on top of an iron oxide-rich surface. The carbon-rich top surface forms during the tribological decomposition of Braycote 601 grease and contains fluorine and sodium from the grease [7, 8]. The Raman spectrum of the carbon-rich coating is reported in the Raman spectroscopy section. Below the carbon-rich coating is the black tribological iron oxide-rich coating that also contains fluorine from the grease. At the end of the sputtering cycles, sodium was no longer present and chromium was observed in both locations in addition to carbon oxygen, fluorine, and iron (Figure 10).

Metallography

A black ball and a segment of the race from the blackened bearing, S/N V6L009, were metallographic cross sectioned and the tempered martensitic 52100 steel and black tribological coating examined (Figure 10 and 11) [5]. The microstructure of the black ball was consistent with properly processed 52100 temper martensite with finely dispersed carbides with a hardness of $R_c$ 64-65 from the surface into the ball. Tapered sections showed no evidence of annealing below the black tribological coating therefore the temperature of the ball did not go above 204°C during the formation of the black tribological coating. The black coating appears to be a micron or two thick. Pits present on the cross–section were very shallow.

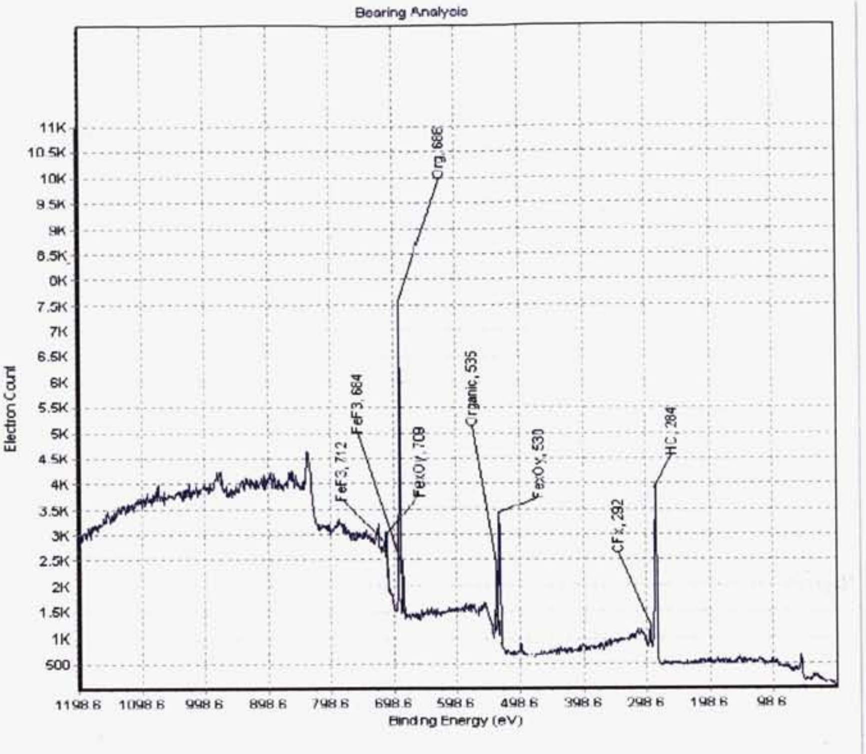

Figure 10. An XPS spectrum for black ball

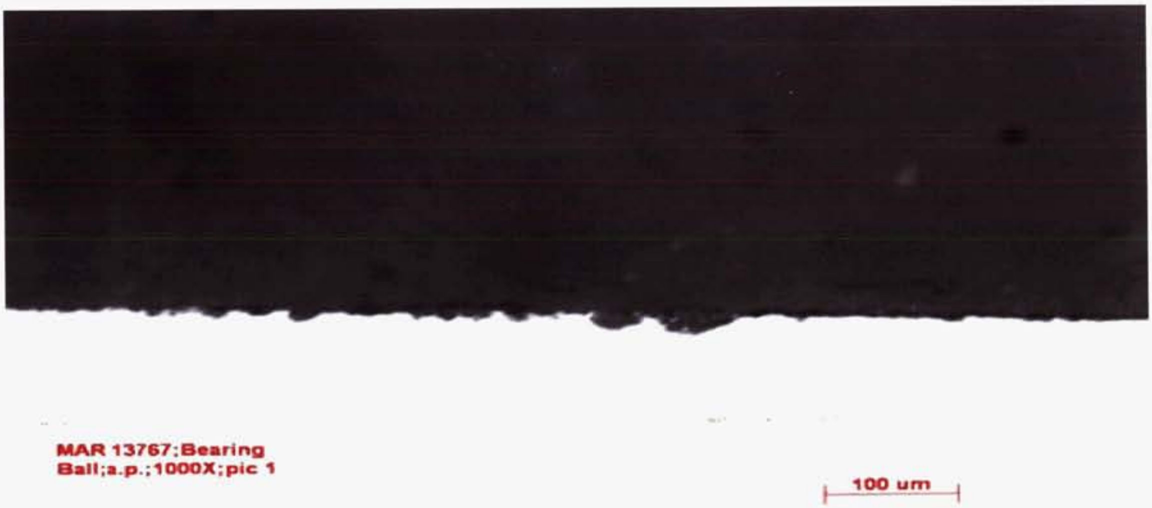

Figure 11a. Metallographic section of black bearing

**Figure 11b. Metallographic section of black bearing**

### Metrology of Previously Flown Flight Bearings

After the discovery of the bearing with the blackened balls, seven additional BF shaft bearings were microscopically inspected and the wear depth profiles were measured. Wear was measured using a form-Talysurf measurement machine. Microscopic examination and wear depth results for these bearings are reported in Table 1. The bearings had mild surface distress but no spalling. The bearings appeared to be highly loaded with ball tracks running near the raceway shoulder. The balls showed discoloration, superficial rust stains but only S/N V6L009 was contained the black tribological coating on the ball and race wear surfaces. Metrology results show that Shuttle flights produced wear depths ranging up to 5 micrometers. The most damaged bearing was S/N V6M002. This bearing had 5 micrometers maximum wear on the inner race with evidence of plastic deformation in raceways.

**Table 1. Results of Metrology of Flight Body Flap Actuator Shaft Bearings**

| Bearing Size | Bearing Serial Number | Number of Flights | Wear Depth Range (micro meter) | Microscopic Observations |
|---|---|---|---|---|
| 106 | V6M002 | 20 | 5.08 | Mild discoloration |
| 108 | V6L009 | 20 | 2.23 | Black complex oxide on balls and wear track |
| 108 | V89E006 | 19 | 2.23 | Light gold color discoloration |
| 108 | V6L007 | 30 | 2.03 | Superficial rust stains |
| 108 | V6L025 | 32 | 1.27 | Slightly darken balls |
| 106 | V6M014 | 30 | 2.03 | Moderate surface distress corrosion |
| 106 | V6L013 | 32 | Wear debris build-up | Moderate surface distress, discoloration likely to lubricant degradation |
| 106 | V6L001 | 19 | .38 | Ball banding and mild discoloration and balls and races |

## Bearing Testing of Body Flap Actuator Bearings

A pre-existing test rig (Figures 12 and 13) was adapted to conduct life tests on the body flap output shaft bearings (Size 106). The bearing tester supported an angular-contact bearing on each end of the drive shaft. Axial load was applied to the bearing pair and shaft by a locking mechanical screw. A drive pulley was attached to the middle of the drive shaft and was driven by a variable-speed AC motor. The bearing housing temperature was controlled by circulating ethylene glycol through coolant passages in the bearing test housings, which raised the test bearing temperature up to 70°C. During testing, the bearing axial load, shaft rotational speed, motor amps, and temperature of bearing outer races were monitored and recorded.

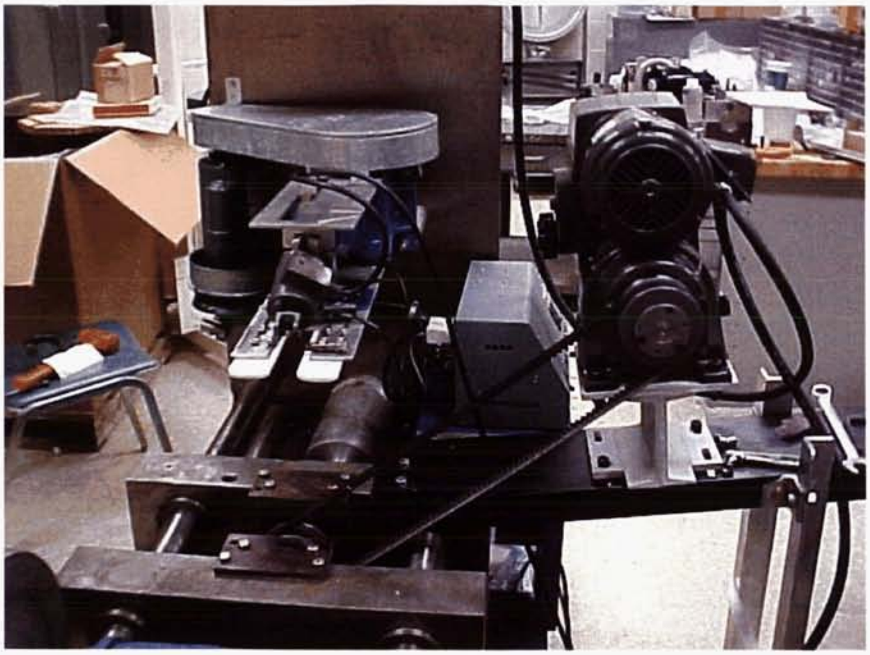

Figure 12. MSFC Bearing Test Rig

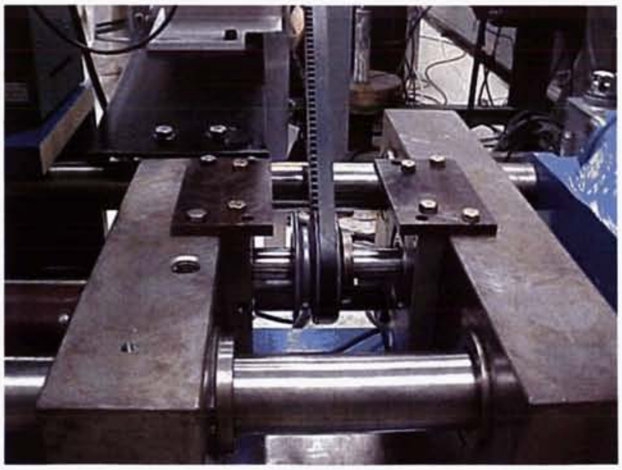

Figure 13. Close-up view of MSFC Bearing Testing Rig

48 Mission Life Test Results at 60°C

The objective of the testing was to demonstrate that previous flown and re-lubricated was acceptable for 12 additional shuttle flights with a safety factor of 4. The temperature of 60°C was selected because it was thought that Braycote 601EF grease was shorter at higher temperature and 60°C was the highest and only temperature recorded in BF actuator system, namely in the power distribution unit.

The life test conditions for a single mission were derived from the flight load spectrum for the body flap actuator as understood early in the test program. The body flap qualification test load spectrum was made worst case to establish the single-mission life test load profile for the body flap input shaft bearings shown in Table 1.

**Table 2. Single Mission Load Profile**

| Cycle | Axial load (N) | Speed (rpm) | Time (seconds) | Temperature (°C) |
|---|---|---|---|---|
| 1 | 15569 | 80 | 1620 | 60 |
| 2 | 18238 | 70 | 90 | 60 |
| 3 | 19572 | 60 | 60 | 60 |
| 4 | 22241 | 50 | 30 | 60 |

With a limited supply of post-flight bearings available, initial test were performed on commercial bearings with similar dimensions to the flight bearings. Balls and cages were removed from the commercial bearings and 18 matched balls were added to make full complement test bearings, i.e., no ball separators. As shown in Table 1, S/N V6M002 had a maximum wear of 5.08 micro meters, which was higher than the other flight bearing. Two commercial bearings were loaded to 26700 N and operated for 10 minutes at 72 rpm to produce wear similar to wear measured in Shuttle flight bearing after 20 to 30 missions. After this testing, the maximum wear on a test bearing (BF-003, Table 3) was found to be 4.45 micro meter. These damaged bearings were cleaned, re-lubricated with Braycote 601EF and successfully tested for 24 hours or 48 mission life at 60°C. The bearings successfully completed this testing and about 1.27 micrometer of additional wear was observed BF-003. During testing no evidence of degradation of bearing performance was observed. Post-test inspection and metrology of the bearings showed moderate additional wear in the bearings as shown in Table 3.

**Table 3. Commercial Bearing Wear after about 25 Missions of Simulated Flight and after an Additional 48 Missions of Life testing**

| Test Serial Number | Max. Wear Depth during Flight Simulation (micro meter) | MSFC Life Test Number | Max. Wear after 48 mission life test (micro meter) |
|---|---|---|---|
| BF-001 | .66 | LT002 | 2.54 |
| BF-003 | 4.45 | LT002 | 5.72 |

A photograph of a ball from BF-003 is shown in Figure 14. The photograph showed some banding and blue discoloration due lubricant degradation. The test lubricant was found to be in good condition. It was creamy white in color with some brown red areas caused by the early stage of lubricant degradation.

**Figure 14. Ball from BF-003 after 48 Mission life test**

Two additional 48 mission life tests were performed on previously flown flight bearings. The results of this testing are shown in Table 4. Both tests were successfully completed. No indication of lubricant failure or severe wear was observed. During the life testing, all bearings performed without anomalies and no evidence of torque increase was observed with increasing test time. In addition, no rise in bearing operating temperature was observed, which also indicated no gross degradation in bearing performance. Post-test inspection of these bearings showed moderate additional wear (Table 4). No evidence of lubricant failure, severe wear and or fatigue spalling was observed.

**Table 4. Wear for flight bearings after Shuttle Flights and after 48 missions of Additional Life testing**

| Test Serial Number | Max wear before test (micro meter) | Max wear 48 mission life test (micro meter) | MSFC Life Test Number |
|---|---|---|---|
| V6M014 | 2.03 | 2.03 | LT003 |
| V6L013 | Wear debris build up | .51 | LT004 |
| V6L001 | .38 | Wear debris build up | LT004 |

After testing, the lubricant appeared to be in good condition. The grease in the bearings was still creamy white with only a few areas of reddish brown discoloration (Figure 15). Balls from flight bearing showed significant banding due to normal wear and possible lubricant degradation (Figure 16).

**Figure 15. Flight bearing S\N V6M013 after 48 mission life test**

**Figure 16. A ball from flight bearing V6L001 after 48 Mission of life tests**

Results of this 48 mission life test showed that 3 previously flown flight bearings and 2 pre-damaged commercial bearings successfully passed life testing for 24 hours or 48 missions at 60°C. Based on these results, it was recommended that freshly re-lubricated, pre-flown body flap shaft bearings were acceptable for 12 more flights on the Space Shuttle with safety factor of 4. When the average operation time per mission was updated to 16 minutes per mission, the bearings were found to be acceptable for 22 missions at 60°C. This recommendation was based on the assumption that 60°C was the worst-case condition for bearing lubricant life. Subsequent testing proved this assumption to be incorrect.

### Life Testing of the Body Flap Shaft Bearings

The 48 mission life testing did not reproduce the black tribological coating on shaft test bearings, so testing with partially lubricated bearings, different temperatures, speeds, and stop-start speed profiles was continued in an attempt to produce the black tribological coating on the bearing wear surfaces, i.e. S/N V6L009. The investigators were surprised to find the life of the bearings to be 10 to 20 hours rather than the 66 hours originally required for the BF actuators. Shaft bearing life testing was redirected to measure the life of the bearing and demonstrate that 12 more Shuttle missions could be successfully accomplished.

In general, it was assumed the blackened balls were generated due to high local temperature, possibly due to lubricant degradation, and\or starvation or from an external heat source during re-entry. The objective of this testing was to generate blackened ball similar to those observed on BFA shaft bearing

S/N V6L009. A second objective of the testing was to determine the lubricant life of Braycote 601 grease used in BFA shaft bearings.

Life Test Conditions:

1. Size 106 commercial 52-100 steel thrust bearings were life tested.
2. A shaft with bearings mounted on the ends was thrust loaded with a locking mechanical screw.
3. The drive shaft was rotated by an electrical motor driving a pulley mounted on the shaft.
4. The bearings were tested in air at room temperature.
5. The criteria for end of bearing life were the onset of a dropping preload, bearing temperature rise, laboring of the drive motor and the onset of severe wear in the bearing.

The initial testing was performed at room temperature with continuous shaft rotation at 50 rpm. Tests were run at several thrust load levels. The tests were allowed to run until lubricant failure was detected. The results of testing are shown in Table 5.

**Table 5. Body Shaft Bearing Life Test Results Using Commercially Equivalent Bearings**

| Bearing Number | Load(N) | Temp (°C) | Time(hr) | Cycles (Krev) | Failure Mode |
|---|---|---|---|---|---|
| 4x Test (3 flight brgs and 2 test brgs) | Mission profile see Table 2 | 60 | n/a | 112.8 | 24 hrs, No failures |
| BF011 | 15569 | 23 | 11.3 | 33.5 | Lubricant failure, Severe wear |
| BF012 | 15569 | 23 | 19 | 57 | Lubricant failure, Severe wear |
| BF013 | 15569 | 23 | 26.3 | 78.9 | Lubricant failure, Severe wear |
| BF09 | 20017 | 23 | 16.9 | 50.7 | Lubricant failure, Severe wear |
| BF010 | 20017 | 23 | 16.9 | 50.7 | Lubricant failure, Severe wear |
| BF008 | 22271 | 23 | 12.8 | 38.4 | Lubricant failure, Severe wear |

Bearing failures (lubricant failure) were observed much earlier than expected. These failures occurred much sooner than in previous 60°C, 48 mission life tests where no failures were observed. The mechanism continued to operate, but significant drops in axial load and bearing temperature increases were observed as well as copious amounts of wear debris. Post-test microscopic examination of the bearings showed two distinct wear modes.

1. Normal Wear Mode Characteristics
    a. Race Appearance - Microscopic examination of the wear tracks in the races revealed a smooth matte finish. In some cases, the wear track was bronze colored. The bearing fabrication grinding marks were worn away.
    b. Ball Appearance - The balls possess a shiny finish like a new ball. The shiny balls surface are often coated with a thin smeared black film covering the balls or concentrated in a wear ring pattern. The wear rings are produced when the rolls around a single axis.

2. Severe Wear Failure Mode (typical of failed bearings)
    a. Race Appearance - Microscopic examination of the race wear tracks showed very rough surface. Wear scars form across the direction of ball motion. At higher loads and longer bearing lives, radial wear scars develop between the wear tracks and the shoulder and metal wear debris deposits on the bearing shoulder. Steel wear debris transfers from ball-to-race and/or race-to-ball. As the bearing test time in the severe wear mode increased to about 60 minutes, the transferred wear deposits turns black. The wear depth increased from 3 micrometers for normal wear to about 80 micrometers for severe wear.
    b. Ball Appearance - undulating rather than smooth ball surfaces were observed. As the test time in the severe wear mode increased to about 60 minutes, the balls turned black.

> Apparently, the black surface was formed when the worn balls heated up and oxidized during the last few minutes of the test.

In general, failed bearings exhibited severe wear. A failed bearing is shown in Figure 17 and 18. The onset of wear started when the lubricant between the ball and race was completely consumed or degraded. Shear plastic deformation occurred between the race and ball steel to cause adhesive wear or severe wear. Due to high friction and heat generation, the local ball temperatures rapidly increased and caused oxidation and discoloration of bearing balls. In some case, the balls were highly discolored and almost black. The test lubricant in the failed bearings was very dark in color with significant degradation and metallic wear debris.

**Figure 17. Failed Test Bearing BF012**

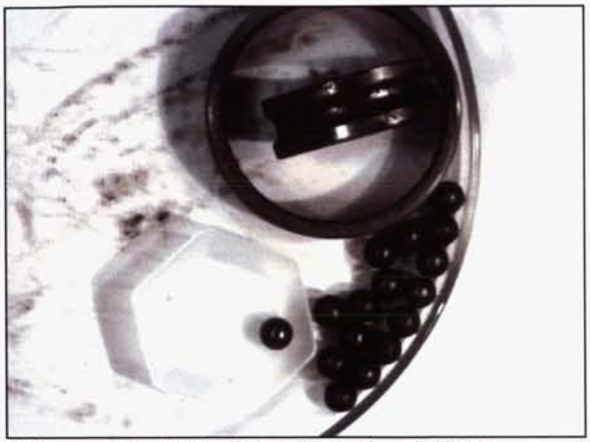

**Figure 18. Failed Test Bearing BF012 (disassembled)**

Darkened balls that were produced in testing were not identical to the black ball from V6L009. Scanning Electron Microscope examination of a failed test ball showed a texture surface. The surface of the test bearings did not have a polished finished, but appears to have been smeared with transferred steel. Some microspalling and surface cracking was observed. The flight bearing with the blackened balls (S/N V6L009) was in fairly good shape. This flight bearing did not exhibit severe wear. Balls had smooth surfaces and the raceway wear track was covered with smooth black oxide coating.

Life Testing at Elevated Temperature

Due to these unexpected results of lower life at room temperature, life tests at elevated temperatures were performed to confirm this trend. Tests were run at 60°C with 15569-N axial load at 50 rpm continuous shaft rotation. One test was run at 70°C under the same conditions. The same bearing test rig as previously described was used. The results are shown in Table 6 and Figure 20.

**Table 6. Results of Continuous rotation testing at elevated temperature**

| Bearing Number | Load (N) | Speed (rpm) | Temp (°C) | Time (hours) | Cycles (Krev) | Failure Mode |
|---|---|---|---|---|---|---|
| BF015 | 15569 | 50 | 60 | 65.35 | 196 | Lubricant failure, Severe wear |
| BF017 | 15569 | 50 | 60 | 39.65 | 119 | Lubricant failure, Severe wear |
| BF031 | 15569 | 80 | 70 | 56.52 | 271 | Lubricant failure, Severe wear |

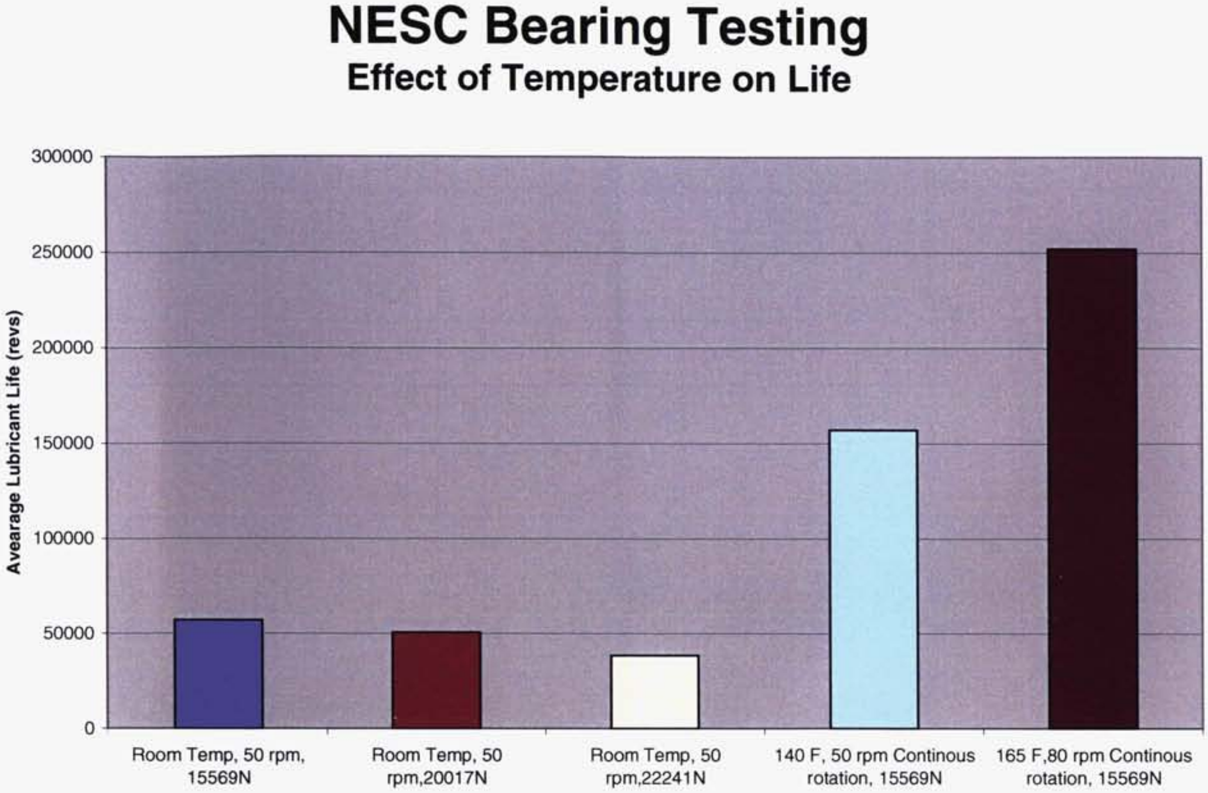

**Figure 20. The effect of temperature on lubricant life**

The results of this testing indicated that temperature had a significant effect on bearing life. Increased temperature yielded a significant increase in bearing life. The cause of this effect has not been determined. One theory is the higher temperature afforded better lubrication either by a decrease in apparent grease viscosity or by an increase in oil separation rate. This resulted in more oil available in wear contact area thus extending bearing life.

### STOP\START Testing at Room Temperature

The testing to determine the lubricant life was performed with continuous rotation. This differs from the 48 mission life tests that had been previously performed in several ways. In the 48 mission life testing, the bearing ran at several different speeds and loads. Also, in actual BFA operation the actuator is operated for short periods of time (several minutes) then sits stationary for extended periods (months). To evaluate the effect of start\stop operation on the extension of bearing life, a series of stop\testing was performed using the same bearing test rig as previously described.

For this testing the bearing rig was run for 30 minutes at 80 rpm shaft rotation and then held idle for 30 minutes. This cycle was continuously repeated until bearing failure occurred. For a baseline comparison three additional tests were conducted with continuous rotation at 80 rpm. The results of this testing are shown in Table 7 and Figure 21.

These results showed start\stop operation has a moderate effect on lubricant life. The average bearing life for stop\start tests was 92500 revolutions which was about 30% greater than the average bearing life for the continuous rotation testing, most probably because surface tension pulls lubricant into the wear track while the bearings were stopped. These results also show that shaft speed had moderate beneficial effect on bearing life most probable because more lubricant was squeezed out of the ball race contact at lower speeds.

**Table 7. Results of Start|Stop lubricant life testing**

| Bearing Number | Load (N) | Temp (°C) | Speed (rpm) | Time(hr) | Cycles (Krev) | Failure Mode |
|---|---|---|---|---|---|---|
| BF019 | 15569 | 23 | 80 | 20.1 | 96.5 | Lubricant failure |
| BF021 | 15569 | 23 | 80 | 13.55 | 65 | Lubricant failure |
| BF023 | 15569 | 23 | 80 | 14.76 | 51 | Lubricant failure |
| BF026(start/stop) | 15569 | 23 | 80 | 23.8 | 114 | Lubricant failure |
| BF028(start/stop) | 15569 | 23 | 80 | 21.31 | 102 | Lubricant failure |
| BF030(start/stop) | 15569 | 23 | 80 | 12.8 | 61.4 | Lubricant failure |

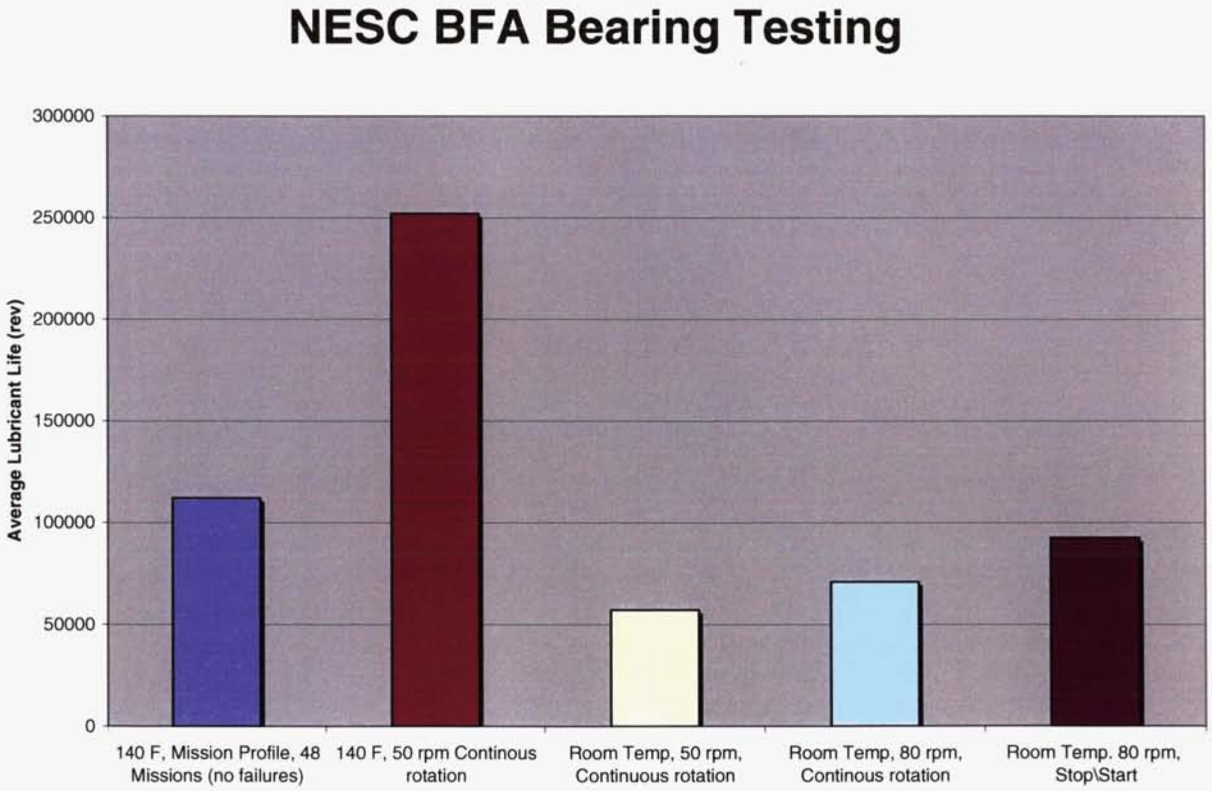
NESC BFA Bearing Testing

**Figure 21. Results of start\stop lubricant life testing**

The start\stop testing at 80 rpm most closely simulated the actual BFA operation. The majority (92%) cycles on the BFA are applied during ground operation under stop\start conditions. All of these cycles occurred at 80 rpm with 15569-N axial load at room temperature. The remaining cycles occurred during flight. The BFA was never operated under maximum load (22241-N load). This load occurred during ascent when the actuator is in a lock position. The actuator was operated for several seconds in space to test the actuator, but the remainder of cycles occurred during re-entry where temperature probably reaches around 60°C. Recent reexamination of the BF actuator operation time line by the NESC showed that the actual average mission actuator operating time was 16 minutes (1280 cycles) rather than the 24 minutes. Based on these facts, the shortest lived start\stop test of 12.8 hours (61.4 cycles) was used to life the BFA shaft bearings. This calculation yielded a bearing life of 12 missions including a safety factor of 4.

## Conclusions

1. Initial test results of full scale bearing testing at 60°C indicated that previously flown and re-lubricated Body Flap Actuator shaft bearings were acceptable for 22 Shuttle Missions with a safety factor of 4. Subsequent bearing testing at 23°C show the lubricant life is reduced at lower operating temperatures.
2. Results of full scale bearing stop\start testing at 23°C showed that new bearings were acceptable for 12 Shuttle Flights with a factor safety of 4.
3. Efforts to duplicate the blackened balls observed on one of the Shuttle Body Actuator shaft bearings were unsuccessful. The blackened balls were produced in testing, but only after lubricant failure and severe wear are initiated. SEM analysis showed that the test blackened balls are not very similar to the flight ball. The test blackened balls were in much worse condition and had a more textured surface with smalls cracks observed. The flight bearing with blackened balls did not suffer a lubricant failure. The flight blackened bearing was in relatively good condition with smooth wear surface.
4. The Raman Spectroscopy, XPS and EDS analysis of the flight black ball detected the presence of carbon-rich layer on an iron oxide-rich layer and both with fluorine. The detection of amorphous carbon, fluorine and $FeF_3$ in both the carbon-rich surface layer and the iron oxide under layer were significant since local degradation of the PFPE lubricant appeared to be in part responsible for the black coating observed on the balls and raceways of P/N 5902050, S/N V6L009, bearing removed from S/N 402 BF actuator. The origin of the thicker, black iron oxide-rich layer under the carbon-rich layer is not well understood. Because it occurred only on the wear surfaces, the tribological chemical reactions in the ball/race wear interface did cause the black coating. Most investigators felt that high temperatures below 200°C contributed to the black coating formation. Local lubricant starvation within the ball path of the bearing may have generated local heating with temperatures high enough to cause the remaining lubricant film to degrade and react with the 52100 steel surface, effecting formation of a complex oxide layer that resulted in the black coating on the wear surfaces. While the system may have recovered locally after the blackened coating event, the oxide layer formed was apparently effective in separating the working surfaces of the bearing, preventing its failure, and serving as a surrogate solid film lubricant.
5. The strength, geometry, metallurgical structure and wear of the black coated bearing were found to be essentially identical to other BF shaft bearings after Shuttle flights. No evidence of severe wear was observed. Therefore, shaft bearings with black tribological coatings like S/N V6L009 are expected to perform successfully for at least 12 more Shuttle missions.
6. The severe wear mode caused failure of the shaft bearing and determined the bearing life. The onset of severe wear is thought to be caused by ball/race metal adhesion after all the Braycote 601EF grease is depleted from the interface.

## Lessons Learned

1. When space mechanisms are qualified by accelerated life testing, bearings should be qualified by real-time life testing. Bearings enduring the highest stresses, longest operating lives or highest temperatures in the mechanism application should be life tested as part of the qualification process.
2. Bearing life and lubricant life was found to be shorter at lower temperature even though the lubricant tribological decomposes or degrades more rapidly at higher temperature.

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