NUREG/CR-6750
INEEL/EXT-01-00816

Performance of MOV Stem Lubricants at Elevated Temperature

Idaho National Engineering and Environmental Laboratory

U.S. Nuclear Regulatory Commission
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Manuscript Completed: September 2001
Date Published: October 2001

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Prepared for
Division of Engineering Technology
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code Y6593

For sale by the Superintendent of Documents, U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone: (202) 512-1800 Fax: (202) 512-2250
Mail: Stop SSOP, Washington, DC 20402-0001

ISBN 0-16-050979-3

ABSTRACT

This report documents the results of recent tests sponsored by the Nuclear Regulatory Commission (NRC) and performed by the Idaho National Engineering and Environmental Laboratory (INEEL). These tests address the effectiveness of the lubricant used on the threaded portion of the valve stem, where the stem nut turns on the stem. Recent testing indicates that an elevated temperature environment can lead to significant increases in the friction coefficient at the stem/stem-nut interface. Most valve actuator qualification tests are performed at room temperature. Similarly, in-service tests are run at ambient plant temperatures, usually in the 70 to 100°F range. Since design conditions can lead to valve operating temperatures in the 200 to 300°F range, it is important to know whether a temperature-induced increase in friction at the stem/stem-nut interface will prevent the operation of critical valves. Lubricant aging is another phenomenon that might have deleterious effects on the thrust output of a valve actuator. Laboratory experience and field experience both indicate that after long periods in elevated temperature environments, the lubricants may lose their lubrication qualities.

The results from an earlier accelerated aging test are presented. The accelerated aging test identified the concerns the led to the elevated temperature testing. To evaluate elevated temperature performance, five different lubricants on four different valve stems and stem nuts were tested. The test series included collection of baseline data at room temperature, single step temperature tests where the temperature of the test setup was elevated directly to 250°F, and step testing where the temperature was elevated in steps to 130, 190, and 250°F, then returned to 70°F. This research produced the following conclusions:

- The physical characteristics of each lubricant change with increasing temperature, changing the frictional performance of each stem and stem nut.

- The consistency of the stem/stem nut coefficient of friction from one stroke to another changes significantly with increasing temperature.

- The stem/stem nut coefficient of friction can increase significantly at elevated temperature.

- The end of stroke friction behavior is highly dependent on the unique stem/stem nut tested, the lubricant, and temperature.

- Each individual stem and stem nut combination has unique characteristics with regard to variation between strokes, elevated temperature performance, and end of stroke friction behavior.

NRC Job Code W6593

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EXECUTIVE SUMMARY

During the past several years, the Nuclear Regulatory Commission (NRC) has supported research addressing the performance of motor-operated valves (MOVs) installed in nuclear power plants. This research included tests and analysis to determine the capability of safety-related MOVs to close (or open) when subjected to the conditions specified in the plants' design documents. For some safety-related MOVs, these design basis conditions include high flow and pressure loads, high temperatures, and degraded voltage.

This report documents the results of recent tests sponsored by the NRC and performed by the Idaho National Engineering and Environmental Laboratory (INEEL) to address the effectiveness of the lubricant used on the threaded portion of the valve stem, where the stem nut turns on the stem. The effectiveness of this lubricant can impact the thrust output of the valve actuator and reduce the margin for ensuring the performance of the MOV. Recent testing indicates that an elevated temperature environment can lead to significant increases in the friction coefficient at the stem/stem-nut interface.

The tests described in this report evaluate the effects of elevated temperature on the performance of the lubricant used on stem and stem nut configurations that are typical of those used in MOVs in U.S. nuclear power plants. Initially, the research set out to investigate how the coefficient of friction might change as the lubricant ages. The intention was to use elevated temperature to accelerate the aging effect on the lubricant. Baseline tests on an unaged lubricant were performed at both cold and hot conditions to determine the friction coefficient for two lubricants on one stem. The results from these tests showed an unexpected increase in the stem/stem-nut coefficient of friction when the temperature changed from ambient (70°F) to hot (250°F) conditions. To properly account for the unexpected increase in friction, the original lubrication accelerated aging program was postponed while the elevated temperature effect on the lubricants was investigated. The elevated temperature testing consist of the following:

- Perform a preliminary investigation, consisting of a series of tests on two stem/stem-nut combinations using five typical lubricants. The purpose of these tests is to evaluate the effect of a temperature increase from ambient (70°F) to design basis (250°F) conditions on friction at the stem/stem-nut interface.

- Perform additional tests to evaluate the sensitivity of the coefficient of friction to incremental increases in operational temperature. The purpose of these tests is to determine if the temperature sensitive performance is dependent on variations in stem thread geometry and to determine the temperature at which performance of each lubricant departs from room temperature baseline data.

- Based on the results from the above testing, perform the single step temperature sensitivity tests and the incremental temperature increase tests on two additional stem/stem-nut combinations to expand the testing to larger stems and additional stem designs (diameter, pitch, and lead).

- Based on the results from the above testing, provide recommendations for the follow-on stem/stem nut lubrication aging tests to determine how the coefficient of friction and the temperature sensitivity might change as the lubricant ages.

The tests were conducted on the INEEL's motor-operated valve load simulator (MOVLS), an instrumented test stand that provides dynamometer-type testing of valve actuators using load profiles that are very similar to the load profile a valve actuator would experience when closing a valve against a flow load. To support this research, the MOVLS was modified to produce simulated valve strokes with essentially no variation in the stem thrust profile between strokes over the duration of the testing. This allowed us to intermix valve strokes representing design basis conditions with valve strokes representing no or low load quarterly stroke testing and be able to reproduce consistent stem thrust profiles for each type of load.

For elevated temperature testing and accelerated aging of the stem lubricant, the valve actuator was wrapped in heat tape and insulated so as to control the actuator, valve stem threads, and stem nut at the temperature required for testing of the stem nut lubricant. The design configuration allowed operation of the valve actuator without disturbing the heater or insulation.

Test hardware including four valve stems and stem nuts and two electric motor actuator sizes were selected based on their performance in our earlier research documented in NUREG/CR-6100. They were also selected to allow the research to examine elevated temperature effects using several different lead designs, running coefficients of friction, end-of-stroke friction behaviors, and stem nut rotational speeds. Five lubricants commonly used in nuclear power plant MOVs were selected for testing. These included Exxon Nebula EP1, Chevron SRI, Mobil Mobilgrease 28 greases, SWEPCO Moly 101, and LOCTITE N-5000 Anti-Seize.

The purpose of the elevated temperature tests is to evaluate the change in stem/stem-nut coefficient of friction as the ambient temperature changes from normal in-plant temperatures to design-basis temperatures. The test series consisted of two strategies:

- Single-step design-basis tests, where the temperature was taken from 70°F directly to 250°F and then back to 70°F.

- Temperature step tests, where the temperature was increased from 70°F in three steps, typically 130, 190, and 250°F, then returned to 70°F at the conclusion of testing.

Our analysis of the elevated temperature tests looked at the performance of each grease using data from all four stem and stem nut combinations. We included physical observations, consistency in performance among strokes, change with temperature, and change in ESFB. Also included is an evaluation of the characteristic performance of each stem and stem nut combination using data from the five lubricants used. The research resulted in the following conclusions:

- Elevated temperature conditions caused the physical characteristics of each of the lubricants to change. Some lubricants thicken at elevated temperature and some thin, moving away from the loaded surfaces. In some lubricants, elevated temperatures can drive off oily components of the lubricant.

- The consistency of the stem/stem nut coefficient of friction over multiple valve strokes depends upon the unique stem/stem nut and lubricant combination. For some combinations, large variations can occur between valve strokes and breakdown of stem lubrication can occur.

- Operation at elevated temperature can have significant effects on the stem/stem nut coefficient of friction. For many of the stem/stem nut and lubricant combinations, large increases in stem nut friction occurred due to elevated temperature. Some lubricants showed no effect and some combinations produced decreasing friction.

- The end of stroke friction behavior (ESFB) dropped at elevated temperatures for most stem/stem nut and lubricant combination. Some combinations produce increasing ESFB at elevated temperature. The actual value for ESFB and the direction of change in ESFB at elevated temperature is highly dependent on the unique stem/stem nut tested and lubricant tested.

- Each individual stem and stem nut combination appear to have unique characteristics with regard to the amount of variation between strokes, elevated temperature performance, and end of stroke friction behavior.

Performance of MOV Stem Lubricants at Elevated Temperature

1 INTRODUCTION

During the past several years, the Nuclear Regulatory Commission (NRC) has supported research addressing the performance of motor-operated valves (MOVs) installed in nuclear power plants. This research included tests and analysis to determine the capability of safety-related MOVs to close (or open) when subjected to the conditions specified in the plants' design documents. For some safety-related MOVs, these design basis conditions include high flow and pressure loads, high temperatures, and degraded voltage.

This report documents the results of recent tests sponsored by the NRC and performed by the Idaho National Engineering and Environmental Laboratory (INEEL) to address the effectiveness of the lubricant used on the threaded portion of the valve stem, where the stem nut turns on the stem. The effectiveness of this lubricant can impact the thrust output of the valve actuator and reduce the margin for ensuring the performance of the MOV. Recent testing indicates that an elevated temperature environment can lead to significant increases in the friction coefficient at the stem/stem-nut interface. Most valve actuator qualification tests incorporating actual stems, stem nuts, and lubricants, are performed at room temperature. Similarly, in-service tests are run at ambient plant temperatures, usually 70 to 100°F. Since design conditions can lead to valve operating temperatures in the 200 to 300°F range, it is important to know whether a temperature-induced increase in friction at the stem/stem-nut interface will prevent the required operation of critical valves.

Lubricant aging is another phenomenon that might have deleterious effects on the thrust output of a valve actuator. Laboratory experience and field experience both indicate that after long periods in elevated temperature environments, the lubricants may become caked and lose their lubrication qualities. Caked lubricants will likely be more viscous, which might prevent the lubricants from flowing into the region between the threads of the valve stem and stem nut and result in higher friction coefficients. This may cause a reduction in the thrust available from a valve actuator, thus resulting in the inability to either open or close the valve when required. The testing discussed in this report provides a starting point from which we may begin to quantify the effects that aging may have on the behavior of lubricants commonly used on the stems and stem nuts of motor-operated valves.

1.1. Background

In rising stem MOVs, the conversion of actuator output torque to a stem thrust load occurs at the stem nut, as shown in Figure 1. The ratio of actuator torque to stem thrust is generally referred to as the stem factor. For a specific valve stem and stem nut, the only variable in the conversion of torque to thrust is the coefficient of friction, as shown in the following power screw equation.

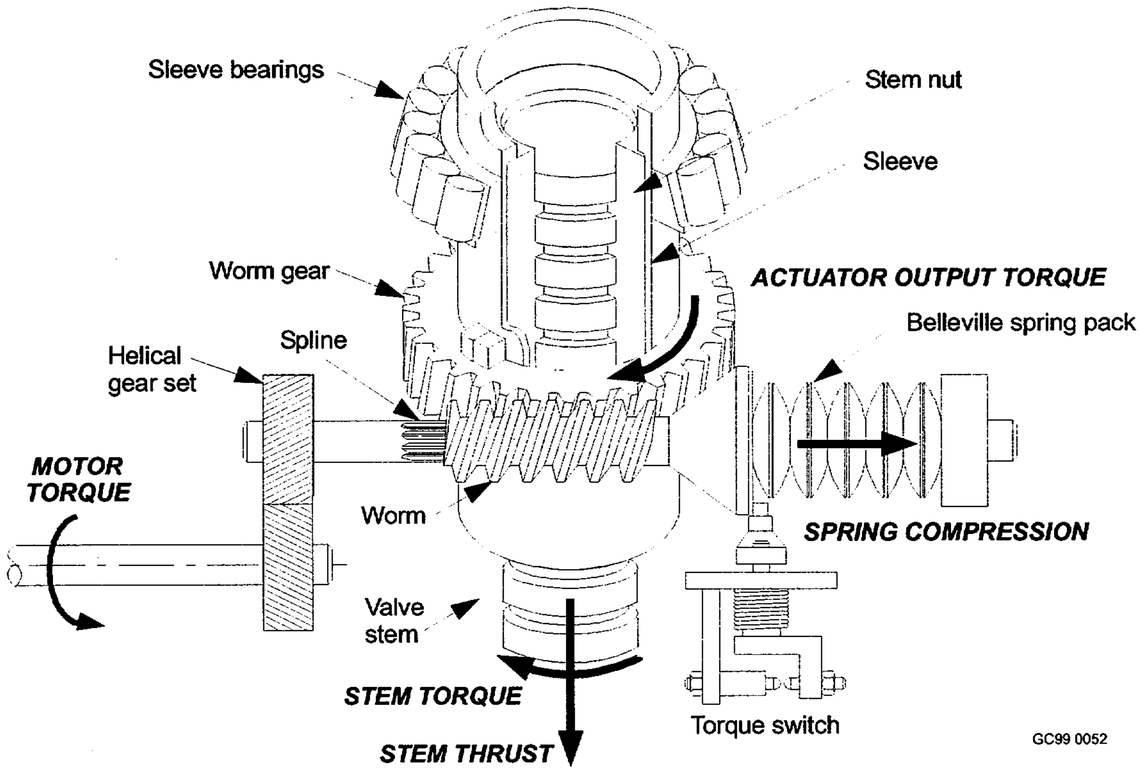

Figure 1. MOV actuator gearbox diagram.

$$\frac{T_{output}}{Th_{stem}} = \frac{d\ (0.96815\ \tan a + \mu)}{24\ (0.96815 - \mu\ \tan a)} = \text{stem factor} \tag{1}$$

where

T_{output}	=	The output torque of the valve actuator
Th_{stem}	=	The valve stem thrust
d	=	OD_{stem} - ½ Pitch
tan *a*	=	Lead/(πd)
μ	=	The stem/stem-nut coefficient of friction
OD_{stem}	=	The outside diameter of the stem
Pitch	=	The distance from the peak of one thread to the peak of an adjacent thread (inches/thread)
Lead	=	The distance the stem travels in one revolution of the stem nut (inches/stem revolution)

This equation is written for U.S. Customary units, where torque is in foot-pounds, thrust is in pounds force, and stem diameter and thread pitch and lead are in inches. The pitch is the distance from the peak of one thread to the peak of an adjacent thread (inches/thread). The lead is the distance the stem travels in one revolution of the stem nut (inches/stem revolution). As an example, if the configuration consists of two threads spiraling the stem instead of one, the lead is different from the pitch. (If only one thread spirals the stem, the pitch and the lead are the same.) The output torque consists of the torque delivered to the stem nut. The stem thrust is the thrust applied to the valve stem to move the stem and valve disc. The ratio of torque to thrust, shown in Equation (1), is the stem factor. The term *d* represents the mean diameter of the stem in terms of the thread contact area, treated as the midpoint of the depth of the thread. The design of Acme power threads is such that the depth of a single thread is equal to half the pitch, so *d* is equal to the outside diameter of the stem minus ½ the pitch (¼ the pitch on one side, and ¼ the pitch on the other side). The term tan *a* is the slope of the thread. The term *0.96815* is a constant in the Acme power thread equation, representing the cosine of half the thread angle (14.5 degrees for Acme threads). The value *24* (2×12) in the numerator represents the *d/2* calculation that provides the mean radius of the stem, combined with the conversion from inches to feet; stem measurements are in inches but torque values are in ft-lb.

The mean stem diameter, the thread pitch, and the thread lead for any stem/stem-nut configuration are constants in the power thread equation. The only variable is the coefficient of friction at the interface between the stem and the stem nut.

1.2. Earlier NRC/INEEL Testing

The INEEL has been performing MOV research for the NRC for many years. In 1988 and 1989, the NRC sponsored the INEEL's full-scale gate valve tests to investigate the valve's ability to isolate a high-energy line break. During those tests (reported in NUREG/CR-5558[1]), we observed that the actual stem friction at the crucial moments in the valve closing stroke (at flow isolation and at torque switch trip) can vary significantly, depending on the load profile applied to the valve before torque switch trip. Figure 2 shows the stem thrust traces from four tests of the same valve, with the same torque switch setting, but with different load histories preceding torque switch trip. In this figure, the sudden increase in stem thrust (larger negative values for compressive stem loads), as indicated by the vertical portion of the trace, is caused when the disc wedges in the seats. The increase in thrust after torque switch trip is caused mostly by motor and gearbox momentum. Flow isolation occurs just before the disc wedges in the seats. The margin is indicated as the difference between the thrust needed for flow isolation and the thrust delivered at torque switch trip.

During 1993 through 1995, we performed research to determine if the stem factor (the efficiency of the conversion of actuator output torque to stem thrust) could be predicted and bounded from the results of tests conducted at conditions less severe than a design basis test (reported in NUREG/CR-6100[2]). The results of stem factor research effort include the following:

- The observed change in stem thrust at torque switch trip with changing running loads is caused by a change in stem nut coefficient of friction at wedging. This is referred to as "load-sensitive behavior" or "rate-of-loading."

- The coefficient of friction varies with changes in stem load. This is true of both the running portion of the closing stroke and the wedging portion.

- Different lubricants on the stem threads can produce different coefficients of friction, all other conditions being the same.

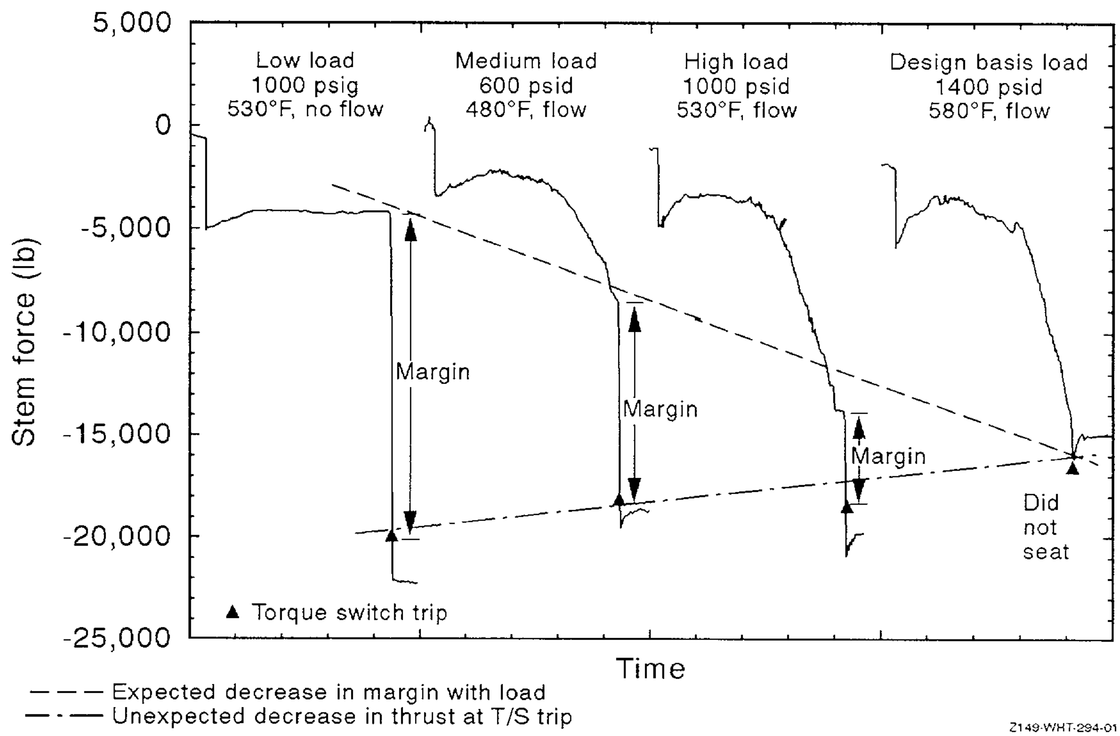

Figure 2. During actual MOV testing, the rate-of-loading changes with stem load.

- Each individual stem/stem nut combination is unique, with its own particular coefficient of friction profile. Some stems are more likely than others to exhibit load-sensitive behavior.

- The running stem-stem nut coefficient of friction exhibits wide scatter at low stem thread pressures, but the trends for each stem flatten out above a thread pressure of about 10,000 psi. Testing at stem running loads above this 10,000 psi threshold should produce measured stem friction values applicable to much higher running loads.

Diagnostic tests of valves in the plants have sometimes indicated stem friction values as high as 0.20. This corresponds with the high end of the default values formerly used in the U.S. nuclear industry. Today, a valve analyst at a U.S. utility would use plant data to justify use of a stem friction value in the range of 0.15. In some cases, a higher default value of 0.20 is necessary. When performing instrumented in-plant tests to determine the actual stem friction for a valve, the analyst must take special care to ensure that the values derived from the in-plant tests are used appropriately and conservatively. These results combined with the NRC/INEEL results show that the stem friction can vary significantly. The variability depends on:

- The particular stem and stem nut configuration. Each stem and stem nut has unique friction characteristics. Some stems show higher friction than others, and some stems show higher friction at lower loads than at higher loads, while other stems show the opposite.

- The brand of lubricant used on the stem. NRC/INEEL testing of two popular lubricants on eight stems showed a difference of about 0.01 to 0.02 in the stem friction. Most of the eight stems performed better (lower friction) with one lubricant than with the other; the difference was greater for some stems than for others.

- Temperature. As the grease temperature increases, it will become less viscous and may not be able to support the stem loads, leading to increased metal to metal contact. As this happens, the friction is likely to change.

- Lubricant aging. As the grease ages, it may dry out, harden, and lose its lubrication qualities. As this happens, the friction is likely to change.

- Load magnitude. During a closing stroke against flow and pressure, the stem friction tends to be different (either higher or lower) at the beginning of the stroke, when the load is low, than later in the stroke just before flow isolation, when the load is higher. Further, the friction tends to be lower during wedging, when the stem experiences a sudden increase in the load, than at the critical moment at or just before flow isolation, when the stem is experiencing a gradual increase in the load.

- Load profile. As shown in Figure 2 (discussed above), the friction at torque switch trip varies depending on the profile of the load that preceded torque switch trip. In general, a large load before flow isolation corresponds with high friction at torque switch trip, while a low load before flow isolation corresponds with low friction at torque switch trip.

1.3. Stem/Stem Nut Lubricant Testing By Others

Lubricant aging on valve stems has not been extensively tested. One test program was conducted by Atomic Energy of Canada Limited (AECL), who performed tests to evaluate the effects of aging on MOV stem/stem nut lubricants used for MOVs in CANDU and Electricite de France (EdF) nuclear power plants. The results of this testing was presented at the Sixth NRC/ASME Symposium on Valve and Pump Testing[3]. This work is based on a single stem and stem nut and did not consider the effects of different stem/stem nut combinations. A lubricant that is best suited for one type of stem/stem nut configuration may not behave similarly for other stem/stem nut configurations under similar environmental conditions. Also, these tests did not age the lubricant in place on the stem and stem nut. Instead, the lubricant samples were oven aged and then the lubricant was applied to the stem and stem nut to be tested. When applied to a stem in this manner, grease that may have dried out and become hardened or began to separate would remix and regain most of the lubricating qualities that may have been degraded by the aging process. This would not be representative to grease aged in a utility. Also, most of the operational tests that were performed were conducted at 77°F, essentially room temperature. Limited testing was performed at accident temperatures, however that data is proprietary.

1.4. Scope of Current Testing

The information included in Sections 1.2 and 1.3 above provides only a brief history of previous testing efforts. As noted above, the previous test results indicated a number of parameters (e.g., lubricant aging) that could affect the proper operation of MOVs.

The tests described in this report evaluate the effects of elevated temperature on the performance of the lubricant used on stem and stem nut configurations that are typical of those used in MOVs in U.S. nuclear power plants. Initially, the research set out to investigate how the coefficient of friction might change as the lubricant ages. The intention was to use elevated temperature to accelerate the aging effect on the lubricant. Baseline tests on an unaged lubricant were performed at both cold and hot conditions to determine the friction coefficient for two lubricants on one stem. The results from these tests showed an unexpected increase in the stem/stem-nut coefficient of friction when the temperature changed from ambient (70°F) to hot (250°F) conditions. To properly account for the unexpected increase in friction, the original lubrication accelerated aging program was postponed while the elevated temperature effect on the lubricants was investigated. The results of the elevated temperature testing will determine if accelerated aging through the use of elevated temperature is feasible. The results will also indicate whether operation at elevated temperature might cause lubricant degradation and higher-than-anticipated coefficients of friction at the stem/stem-nut interface. The elevated temperature testing consist of the following:

- Perform a preliminary investigation, consisting of a series of tests on two stem/stem-nut combinations using five typical lubricants. The purpose of these tests is to evaluate the effect of a temperature increase from ambient (70°F) to design basis (250°F) conditions on friction at the stem/stem-nut interface.

- Perform additional tests to evaluate the sensitivity of the coefficient of friction to incremental increases in operational temperature. The purpose of these tests is to determine if the temperature sensitive performance is dependent on variations in stem thread geometry and to determine the temperature at which performance of each lubricant departs from room temperature baseline data.

- Based on the results from the above testing, perform the single step temperature sensitivity tests and the incremental temperature increase tests on two additional stem/stem-nut combinations to expand the testing to larger stems and additional stem designs (diameter, pitch, and lead).

- Based on the results from the above testing, provide recommendations for the follow-on stem/stem nut lubrication aging tests to determine how the coefficient of friction and the temperature sensitivity might change as the lubricant ages.

2 TEST DESIGN

2.1. Test Equipment

The tests were conducted at the INEEL on the motor-operated valve load simulator (MOVLS), shown in Figure 3. The MOVLS is an instrumented test stand that provides dynamometer-type testing of valve actuators using load profiles that are very similar to the load profile a valve actuator would experience when closing a valve against a flow load. To support the initial stem lubrication aging study, the MOVLS was modified to produce simulated valve strokes with essentially no variation in the stem thrust profile between strokes over the duration of the testing. This allowed us to intermix valve strokes representing design basis conditions with valve strokes representing no or low load quarterly stroke testing and be able to reproduce consistent stem thrust profiles for each type of load. This was accomplished by adding a sight glass to the MOVLS accumulator to precisely control the water level at the start of each stroke. The initial pressure in the accumulator was controlled using a pressure gage. The volume of water in the accumulator and the overpressure at the beginning of the stroke determine the load profile during the stroke. With multiple strokes all beginning with the same overpressure and water level in the accumulator, the thrust-versus-position profiles will all be essentially the same.

For elevated temperature testing and accelerated aging of the stem lubricant, the valve actuator was wrapped in heat tape and insulated so as to control the actuator, valve stem threads, and stem nut at the temperature required for testing of the stem nut lubricant. Figure 4 shows the MOVLS during elevated temperature testing. The design configuration allowed operation of the valve actuator without disturbing the heater or insulation.

The following is a list of the major equipment used in the performance of this research.

- Limitorque SMB-0 actuator equipped with a Reliance 25 ft-lb 480V ac motor
- Limitorque SMB-1 actuator equipped with a Reliance 60 ft-lb 480V ac motor
- Stem 2, 1.750-inch-diameter, 1/4-pitch, 1/4-lead valve stem and stem nut
- Stem 3, 1.250-inch-diameter, 1/4-pitch, 1/2-lead valve stem and stem nut
- Stem 4, 2.000-inch-diameter, 1/3-pitch, 3/3-lead valve stem and stem nut
- Stem 5, 2.125-inch-diameter, 1/4-pitch, 1/2-lead valve stem and stem nut.

The valve stems listed above were selected based on their performance in our earlier research (the names match those used in that work) documented in NUREG/CR-6100. They were also selected to allow the research to examine elevated temperature effects using several different lead designs, running coefficients of friction, end-of-stroke friction behaviors, and stem nut rotational speeds.

It should be noted that NUREG/CR-6100 contains a typographical error that lists the characteristics of Stem 5 shown above as Stem 6. The Stem 5 listing above is correct. This selection of valve stems is intended to allow the research to examine the lubrication heating and aging effects using several different lead designs, running coefficients of friction, end-of-stroke friction behaviors, and stem nut rotational speeds. Stem 2 is a single-lead stem that exhibited running coefficients of friction of 0.12 and end-of-stroke friction behavior (ESFB) in the 16% range when tested with the EP1 lubricant. That is, the coefficient of friction was 16% higher at the end of a high-load stroke, as compared with a low-load stroke. Stem 3 is a double-lead stem that exhibited running coefficients of friction of 0.10 and ESFB in the 20% range when tested with the EP1 lubricant. The rotational speed of the stem nut on Stem 3 is

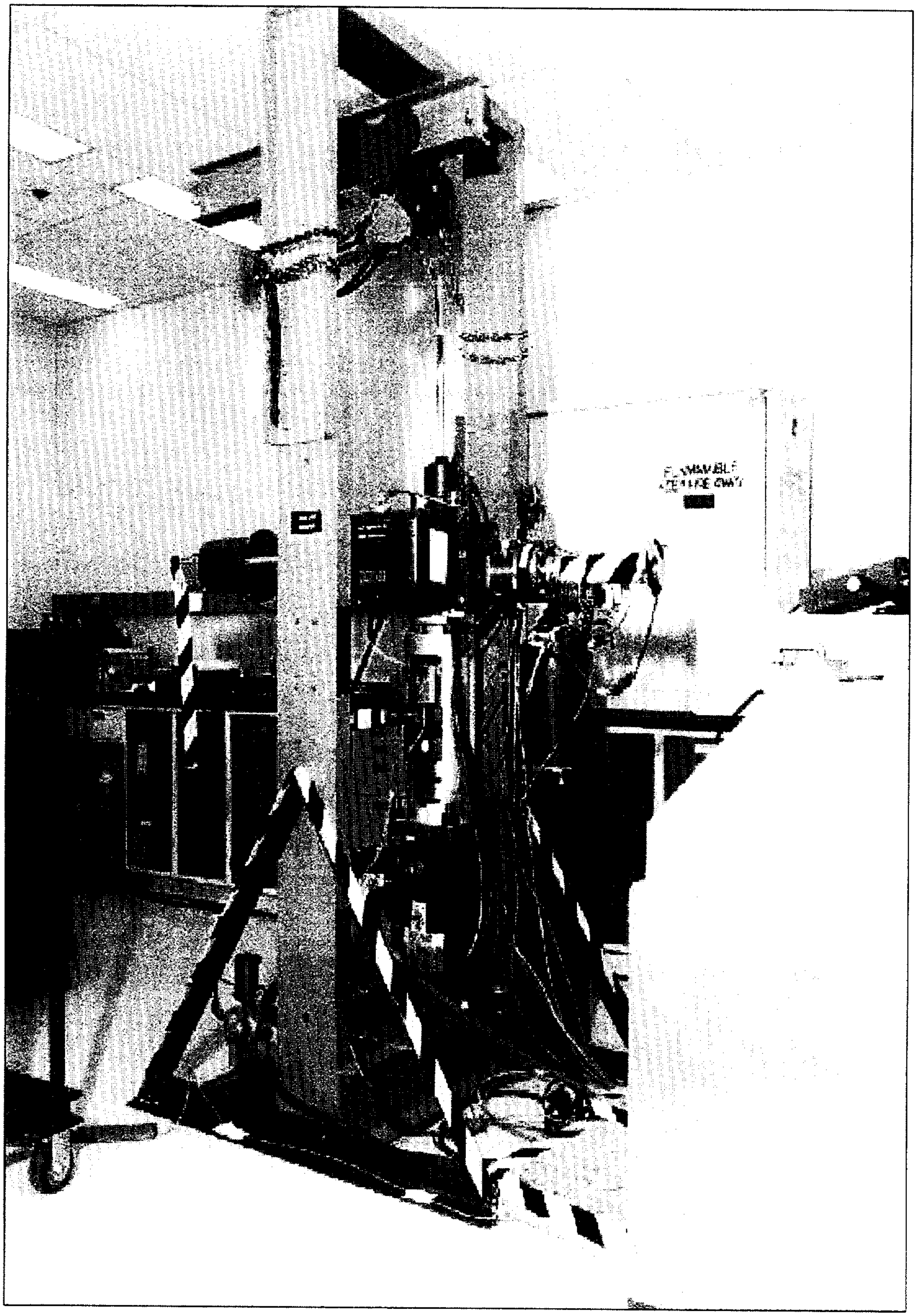

Figure 3. INEEL motor operated valve load simulator (MOVLS).

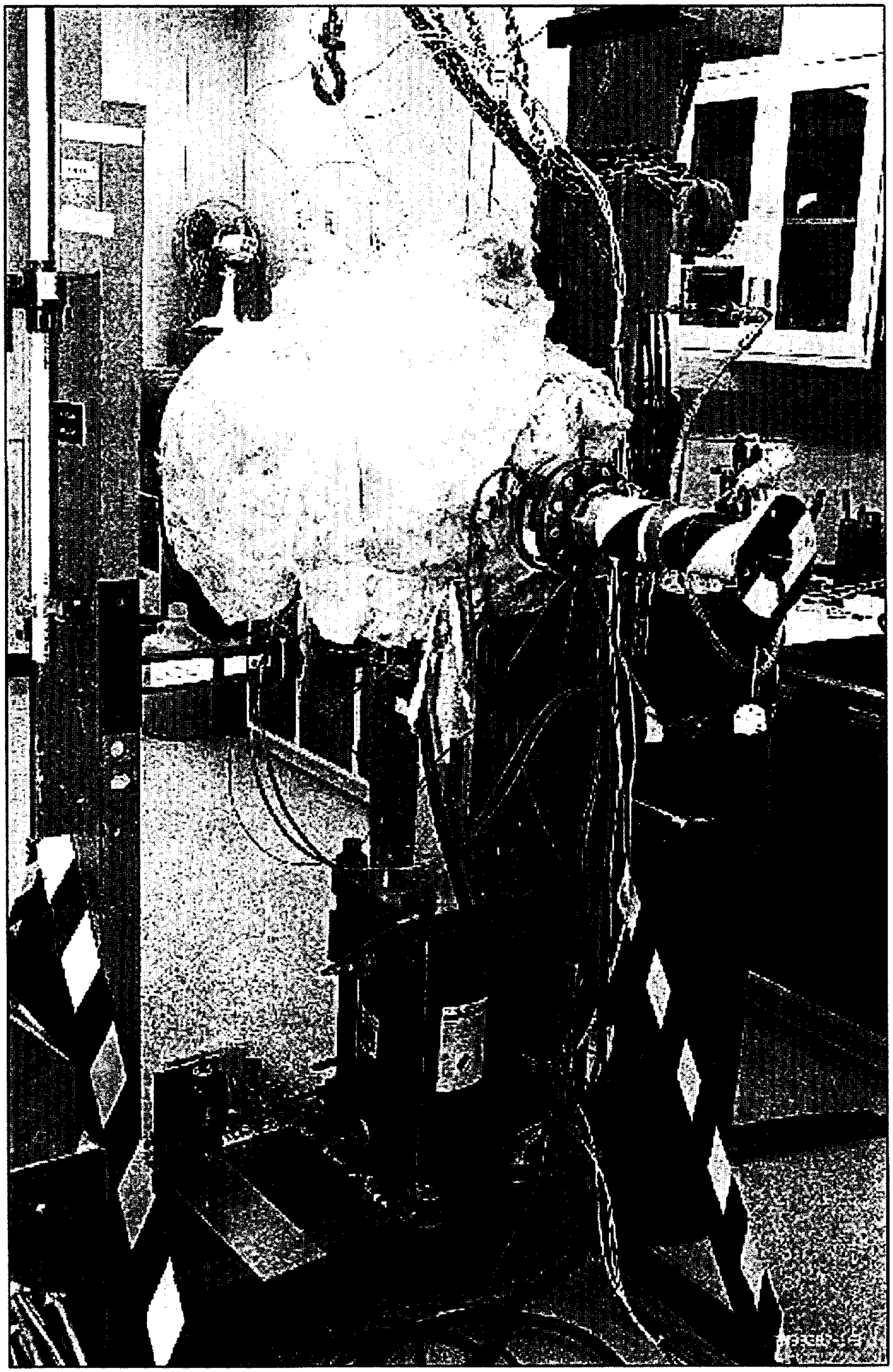

Figure 4. Actuators were heated to design basis temperatures.

about half that of Stem 2. Stem 4 is a triple-lead stem. During the previous INEEL research program, it averaged a 0.11 running coefficient of friction and about 15% ESFB. Stem 5 is a double-lead stem. Previously it averaged a 0.11 running coefficient of friction and about 20% ESFB. All the testing performed under the previous INEEL research program referred to above was accomplished at room temperature.

3 INSTRUMENTATION

During the testing of each stem/stem-nut combination, the temperature of the MOVLS components were monitored using the instrumentation listed in Table 1. The eight thermocouples were strategically placed to allow monitoring of temperatures at various locations throughout the MOVLS. Each of the measurements was recorded at a rate of 600 samples per second by the data acquisition system whenever the actuator was operated. In addition, a chart recorder was used to track two of the temperature measurements throughout the test period.

Table 1. Heater control instrumentation (600 Hz recording frequency).

TCS Channel No.	Description
0	Thermocouple: Grease temperature - side
1	Thermocouple: Grease temperature - top
2	Thermocouple: Operator housing temperature - limit switch
3	Thermocouple: Operator housing temperature - rear
4	Thermocouple: Valve stem temperature
5	Thermocouple: Stem cover temperature
6	Thermocouple: Spring pack temperature
7	Thermocouple: Spool piece temperature

Table 2 lists the instrumentation used to monitor actuator operation during the tests. Electrical measurements for the ac motors included the ac line current and voltage for each phase. Motor output torque and speed were measured using a torque cell and tachometer mounted between the motor and the gearbox. A torque arm attached to the valve stem measured the output torque of the gearbox, and an in-line load cell measured valve stem thrust. Other measurements included actuator torque switch trip, torque spring thrust and deflection, and valve stem position. Each of these measurements was recorded at a rate of 600 samples per second by the data acquisition system whenever the actuator was operated. Calibration of the load cells allows a measurement error ±60 lb. Calibration of the torque arm allows a measurement error of ±4 ft-lb for the small torque arm (Stems 2 and 3) and ±6 ft-lb for the large torque arm (Stems 4 and 5).

Table 2. MOV Stroke Instrumentation (600 Hz recording frequency).

TCS Channel No.	Description
48	Motor current -I1 RMS
49	Motor current - I2 RMS
50	Motor current - I3 RMS
56	Motor speed
32	Motor torque
51	Motor voltage - V1-2 RMS
52	Motor voltage - V2-3 RMS
57	Valve stem position
40	Valve stem torque
41	Valve stem torque
33	Valve stem thrust
58	Actuator torque spring deflection
34	Actuator torque spring thrust
59	Actuator torque switch trip
60	Transformer voltage
35	Accumulator pressure

3.1. Test Matrix

The scope of the testing described above requires several different tests to be run. These tests and the conditions for which the data were used are described in the following paragraphs. The test matrix calls for testing with five lubricants and four stem/stem-nut combinations, for a total of twenty sets of tests.

3.1.1. Lubricants Tested

Prior to each series of tests, the stem and stem nut were removed from the MOVLS and cleaned using a multi-step procedure to remove all traces of the prior lubricant. A fresh application of the next lubricant to be tested was then applied and the stem and stem nut were reinstalled into the MOVLS. Five lubricants commonly used in nuclear power plant MOVs were selected for testing. Descriptions and uses of each were obtained from information published by each manufacturer and summarized below.

Exxon Nebula EP1

Nebula EP1 is recommended for use in plain and anti-friction bearings and other machine elements operating at low to high temperatures, -22 to 302°F (-30 to 150°C). It also resists the washing action of caustic or hot or cold water. It will lubricate bearings operating at 400°F (205°C) if the correct application interval is carefully determined and followed. It is a smooth brown grease with a mild, bland petroleum odor.

Nebula EP type greases are designed to satisfy a wide range of applications. They derive their unique properties from the special calcium complex soap system used in their manufacture. They offer the following features and benefits:

- Inherent extreme pressure properties, obtained without the use of additives,
- High dropping point; they do not melt even above 500°F (260°C),

- Excellent anti-wear, anti-rust, anti-fretting and lubricity under wet or dry conditions, and
- Fewer tendencies to soften with increasing temperature as compared to other greases.

Limitorque approves Nebula EP1 for use in its valve actuators for the nuclear power industry. It has been radiation tested and proven through environment qualification testing for use inside the actuator gearbox.

Chevron SRI

Chevron SRI is a high temperature ball and roller bearing grease. It is recommended for use in a wide range of automotive and industrial applications for use in anti-friction bearings operating at high speeds (10,000 rpm and greater). It is also recommended for use where the operating temperatures are on the order of 302°F (150°C) and higher where there is a likelihood that water or salt water will get into the bearings. It performs satisfactorily in bearings at temperatures as low as -22°F (-30°C).

Chevron SRI is formulated with ISOSYNTM base stocks, a synthetic polyurea ashless organic thickener, and high performance rust and oxidation inhibitors. Its texture is smooth and buttery and its color is dark green. Major bearing manufacturers, along with a number of electric motor manufacturers, recommend or use Chevron SRI. Chevron SRI will outperform most other greases in unsealed electric motor bearings operating in moist conditions, applications where silent operations are called for; also, as a "life-pack" lubricant by manufacturers of automotive generators, alternators, and starters.

Mobil Mobilgrease 28

Mobilgrease 28 is a red synthetic grease with a mild odor. It is designed for the lubrication of plain and rolling bearings at low to high speeds, and splines, screws, worm gears, and other mechanisms where high friction reduction, low wear, and low lubricant friction losses are required. It provides minimum resistance to starting at extreme low temperatures, down to -65°F (-54°C), as well as low running torque. Mobilgrease 28 prevents friction oxidation (fretting) and lubricates rolling element bearings under conditions of high speeds and temperatures. It has also shown superior ability to lubricate heavily loaded sliding mechanisms, such as wing flap screwjacks.

Mobilgrease 28 is also recommended for industrial lubrication, including sealed or repackable ball and roller bearings wherever extreme temperature conditions, high speeds, or water-washing resistance are factors. Typical applications include conveyor bearings, small alternator bearings operating at temperatures near 350°F (177°C), high-speed miniature ball bearings, and bearing situations where oscillatory motion, vibration, and fretting create problems. Advantages include:

- Improved friction reduction, low wear rates, and low lubricant drag,
- Wide temperature range with high thermal stability,
- Compatibility with mineral-oil-base greases,
- Extreme-pressure characteristics, and
- High resistance to water washing.

SWEPCO Moly 101

Moly 101 is a gray general-purpose grease with a lube oil odor. It is a versatile grease designed for low and high temperature, multi-purpose applications. It is recommended for roller bearings, heavy weight on swing gear, and large cranes-lift, clamshell, and draglines with up to 500,000 psi contact pressure.

SWEPCO Moly 101 is a non-melt grease that will not melt at any temperature, containing the technical fine grade Molybdenum Disulfide (Moly Powder). Its optimum performance range is -30°F to 500°F (-34°C to 260°C). It contains SWEPCO's proprietary anti-friction and anti-wear additive, LUBIUM.

LOCTITE N-5000 Anti-Seize

LOCTITE High Performance N-5000 anti-seize is a specially formulated nickel based anti-seize lubricant. Typical applications include bolts, studs, valves, pipe fittings, slip fits, and press fits in nuclear power plants, chemical plants, pharmaceutical plants, paper mills, and other locations where stainless steel fasteners are used. It appears as a silver-gray paste and has the following special features:

- Superior anti-seize: extreme severity anti-seize tests show stuck studs reduced by 90% compared to products recommended for the same use,
- More uniform torque tension: smaller difference in torque coefficients between bolting materials,
- High purity: made from the highest purity ingredients,
- Free from copper: less than 25 ppm copper, and
- Typically used in applications with a dry surface temperature of -20°F to 2400°F (-29°C to 1315°C).

3.1.2. Baseline Tests

The baseline tests provided data from MOVLS setup strokes and test strokes with the lubricant at ambient temperature. No-load/low-load baseline tests are intended to represent typical in-service tests conducted in the power plants. Data from these tests were used to determine the stability of the stem/stem-nut coefficient of friction at these load levels and to establish the ambient temperature baseline values.

For the high-load baseline tests, the actuator torque switch was set to produce a final stem force near the maximum allowed for the valve stem, the actuator, or the stem thrust and torque instrumentation, whichever was the limiting case. The level and pressure in the MOVLS accumulator was determined during the initial setup so that the running load was sufficient to produce a stem thread pressure that exceeded 10,000 psi by the end of the stroke. As discussed earlier in this report, a stem thread pressure threshold of 10,000 psi is needed for the friction coefficient to stabilize. Stem thread pressure is determined using the measured thrust and an approximate thread area based on one stem thread revolution.

3.1.3. Elevated Temperature Tests

Two groups of elevated temperature tests were performed. In the first group of tests, data at elevated temperature conditions of 250°F were collected for comparison with the baseline data. Following the 250°F tests, the actuator was allowed to cool down, and a final set of tests was performed at ambient temperature (70°F).

The second group of elevated temperature tests was performed to investigate the temperature sensitivity of each lubricant by roughly identifying the temperature threshold at which the coefficient of friction departs from the baseline. This second group of tests was conducted by raising the valve actuator temperature in steps and performing five loaded strokes to acquire data at each step. The baseline tests described above provided data at ambient temperature (~70°F). The elevated temperature tests described here collected data at three temperature steps: 130, 190, and 250°F. Following the 250°F tests, the actuator was allowed to cool down, and a final set of tests was performed at ambient temperature (70°F).

Table 3 summarizes the test sequence. The sequence listed in Table 3 has been performed on all of the four stems, with all five lubricants, for a total of twenty sets of tests. In some cases, additional tests were performed to verify behavior that at the time appeared to be anomalous.

Table 3. Elevated temperature test sequence.

Test Type	Description
Elevated Temperature Tests	
Setup tests	Various loads, ambient temperature (multiple strokes)
Baseline tests	High load, ambient temperature (five strokes)
Hot tests	High load, elevated temperature, 250°F (five strokes)
Final tests	High load, ambient temperature (five strokes)
Elevated Temperature Step Tests	
Baseline tests	High load, ambient temperature (five strokes)
Step 1 tests	High load, elevated temperature, 130°F (five strokes)
Step 2 tests	High load, elevated temperature, 190°F (five strokes)
Step 3 tests	High load, elevated temperature, 250°F (five strokes)
Final tests	High load, ambient temperature (five strokes)

4 RESULTS

4.1. Initial Accelerated Aging Tests

As mentioned earlier, two lubricants were tested on one stem as part of the original lubricant aging tests. These initial tests identified a lubricant temperature sensitivity that was not expected. As a result, the lubricant aging tests were suspended and further elevated temperature tests were developed. This subsection discusses the results of those initial lubricant aging tests.

4.1.1. Stem 2 with Exxon Nebula EP1 (Aged)

The first configuration tested under the initial accelerated aging series was Stem 2 with Exxon Nebula EP1. The grease sample was taken from a container that had been on site for approximately 10 years. Neither the grease container nor the MSDS for this grease indicated a shelf life or operational life restriction. The Nebula EP1 sample was applied to the stem and the startup and baseline tests for the aging test series were performed. It was during these tests that the anomalous stem/stem-nut performance was first observed. The following paragraphs discuss five cold tests (ambient temperature, ~70°F) and five hot tests (250°F).

Figure 5 shows the stem thrust traces for the five cold tests. The data show no variation in stem thrust among the five tests, with each stroke beginning about 5,000 lb and increasing to near 10,000 lb thrust. This equates to a running stem thread pressure from 7,800 to 14,900 psi, (recall the 10,000 psi threshold for stable stem-stem nut frictional performance discussed earlier). The stem torque traces for the same five cold tests show consistent performance with no variation among tests.

Figure 6 is a plot of the stem/stem-nut coefficient of friction for the five cold tests. Again the data show consistent performance, with values running at about 0.10, which is similar to the results obtained in the earlier INEEL research program (NUREG/CR-6100).

During the hot tests at 250°F, the actuator failed to complete the stroke on the first of the five strokes, reaching torque switch trip mid-stroke. In order to complete the testing, we reduced the accumulator pressure (which reduces the thrust load imposed on the actuator), and we repeated the test (with a lower running load). The actuator successfully stroked on the second test but again failed to complete the third stroke. We reduced the running load once more, and the actuator successfully stroked on the fourth test but failed on the fifth. The fifth test was accompanied by a loud squealing sound coming from the actuator, apparently from the stem nut. Figure 7 presents the stem thrust traces for the five hot tests, showing the reduction in stem thrust after the first and third tests and the failure to fully close on the first, third, and fifth tests.

The increase in stem/stem-nut coefficient of friction associated with these tests can be seen in Figure 8. The coefficient of friction started out significantly higher than in the cold tests (0.13 compared to 0.10) and continued to increase with each stroke at 250°F. A coefficient of friction greater than 0.20 was observed in the final hot test.

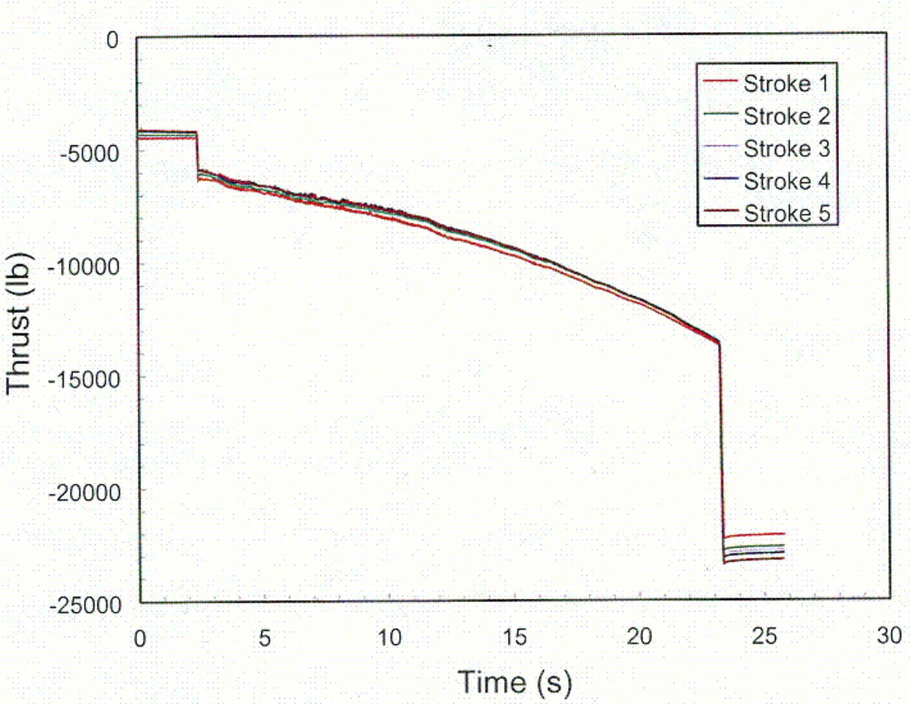

Figure 5. The five cold load tests for stem 2 with EP1 show no variation in the stem thrust between strokes.

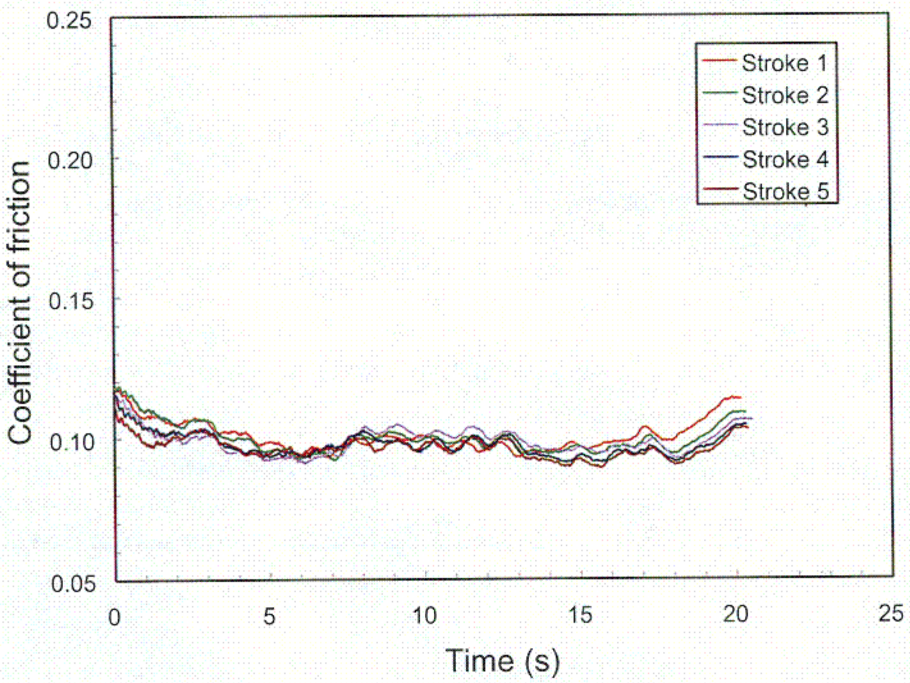

Figure 6. The five cold load tests for stem 2 with EP1 show little variation in the stem coefficient of friction.

C01

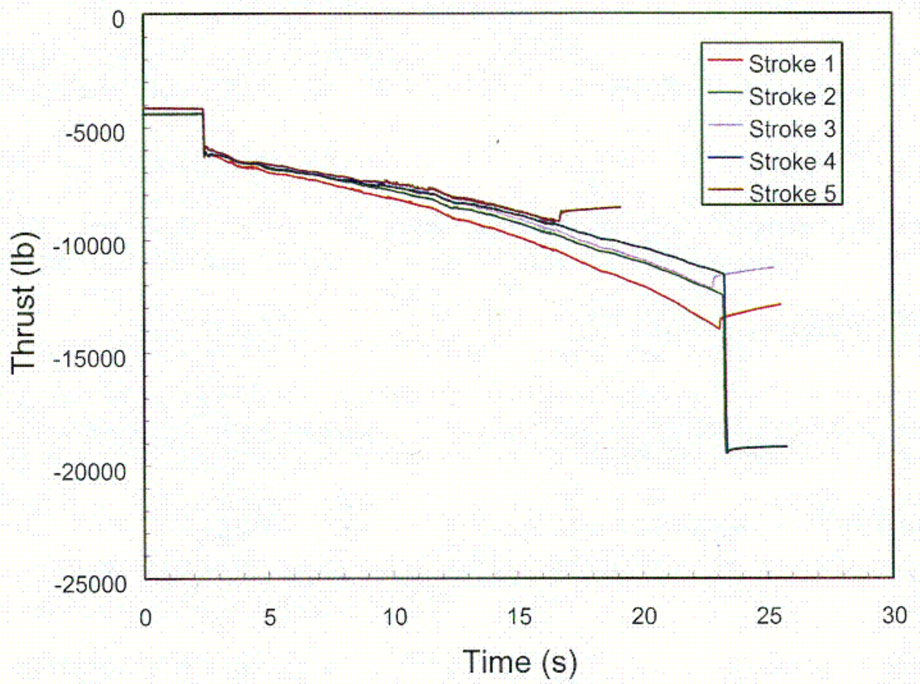

Figure 7. The five hot load tests for stem 2 with EP1 required changes to the MOVLS settings to produce full closure.

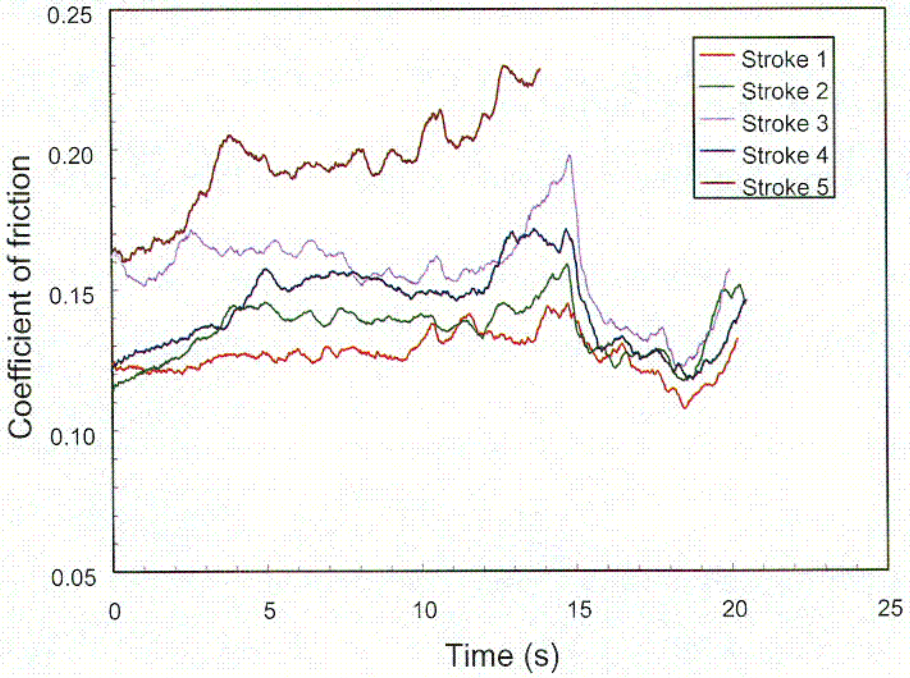

Figure 8. The five hot load tests for stem 2 with EP1 show significant variation in the stem coefficient of friction.

C02

Following the anomalous performance, Stem 2 was removed from the actuator and inspected. Figure 9 is a photograph of Stem 2 with the Exxon Nebula EP1 lubricant immediately after removal from the actuator. The left side of Figure 10 shows a smear of the lubricant taken directly from the original container and from the stem after testing, one sample from the bottom of the stem nut and one from inside of the stem nut. Notice how the lubricant changed from a tan color to dark brown and had hardened due to the elevated temperature conditions. The stem and stem nut were cleaned and inspected, and no damage or abnormal wear was observed on the load-bearing surfaces. Exxon Nebula EP1 was also used as the lubricant inside the actuator gearbox. We inspected the grease inside the actuator gearbox and found it to be near the original color and consistency. The right side of Figure 10 shows a smear from the side and the top ports of the actuator and shows that the lubricant from inside the sealed gearbox does not show the signs of degradation seen on the stem-stem nut.

Exxon Nebula EP1 has been used for stem lubrication in some nuclear plants. Our review of the MSDS indicated that the flash point, melting, and auto-ignition temperatures were well above the accelerated aging temperature of 250°F. The Material Safety Data Sheet (MSDS) states:

- "Nebula EP, in the appropriate consistency grade, is suitable...at high or low temperatures..." and "...Nebula EP tends to retain its consistency with increasing temperatures."
- "This grease is not recommended for applications where continuously high temperatures cause oil separation."

Conversations with Exxon technical representatives indicated that because Nebula EP1 is soap-based, it tends to harden with age. This is one consideration that helps determine the shelf life. The Exxon representatives stated that base oil separation with shelf storage over extended time periods is also a concern and another factor considered in the shelf life recommendation. Exxon stated that the shelf life of Nebula EP1 is two years but does not provide any service life recommendations. The technical representative also stated that use of the grease in applications where it would be "worked" or "mixed" (e.g., a ball bearing or closed gear train) would extend the service life of the lubricant by preventing base oil separation and hardening. Exxon recommends a continuous operating temperature limit of 250°F. They do not publish any in-service inspection criteria; however, most users apply in-service inspection criteria based on visual inspection for color, separation, and hardening.

For use in actuator gearboxes, Limitorque lists Nebula EP1 as one of only two lubricants acceptable for nuclear containment units. The other approved lubricant is Nebula EP0. No service life restrictions are provided, but periodic lubricant inspections are recommended. As long as the lubricant passes these inspections, the grease can remain in the actuator for the qualified life of the actuator. The typical use of Nebula EP1 in actuator gearboxes exceeds the Exxon recommended shelf life. However, the Limitorque environmental qualification at 340°F supports higher temperature. Operating experience and existing test data supports use as a gearbox lubricant beyond the recommended shelf life.

To summarize, at room temperature the stem nut performance was consistent with earlier testing. The observed anomalous stem nut performance was caused by degradation in the lubricant properties at hot conditions. Our Nebula EP1 lubricant had exceeded the recommended shelf life and was used near the recommended operating temperature limit. This recommended shelf life limit is not common knowledge in the nuclear industry. Our data supports the use of the Nebula EP1 lubricant inside the gearbox both at elevated temperature and beyond the two-year shelf life.

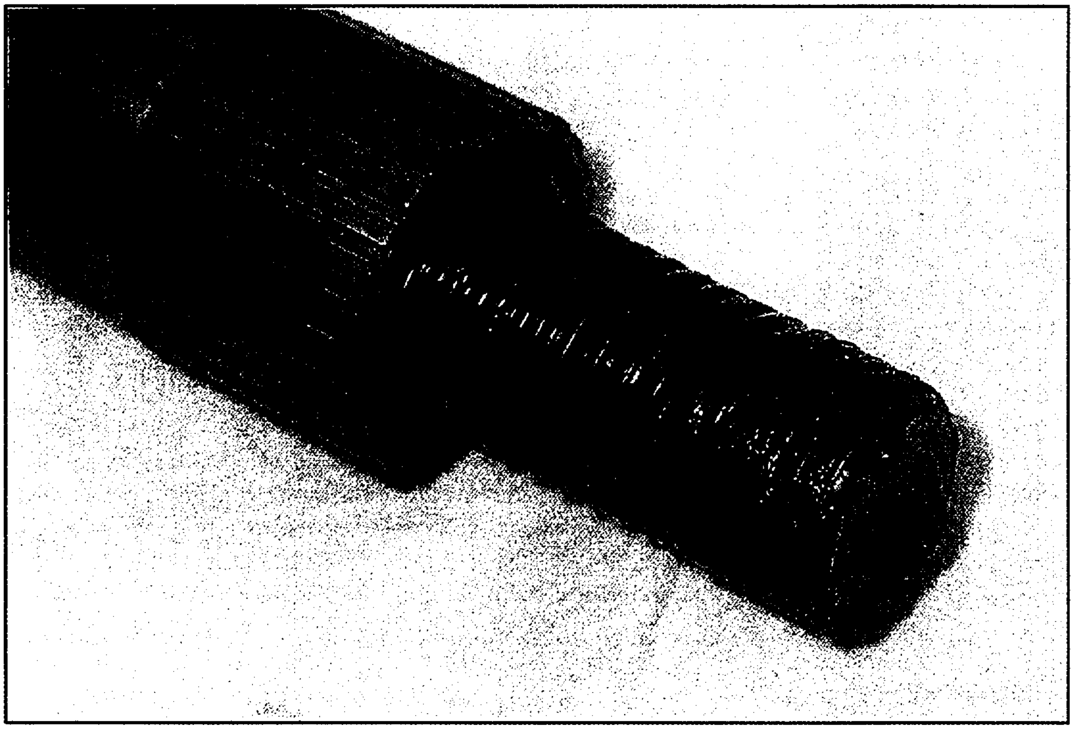

Figure 9. After testing, EP1 changed from tan to brown and hardened.

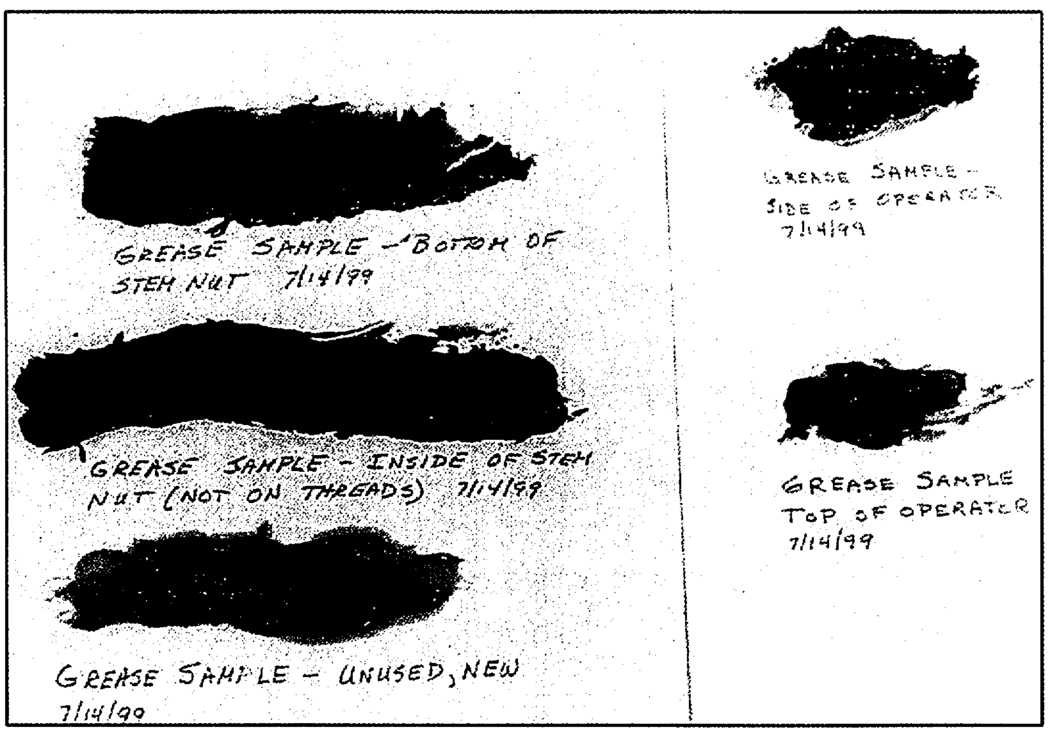

Figure 10. After testing, smear samples from the stem show that the EP1 changed from tan to brown and hardened. Smear samples from inside the sealed gearbox did not change significantly.

4.1.2. Stem 2 with Chevron SRI

The second configuration tested under the initial accelerated aging series was Stem 2 with Chevron SRI. The grease sample was new, purchased specifically for this test program. The following paragraphs discuss five cold tests and five hot tests performed with Chevron SRI.

Figures 11 and 12 show the stem thrust and stem torque traces for the five cold tests. Once again, the data show no variation in stem thrust among the five tests, with each stroke beginning at about 5,000 lb and increasing to near 10,000 lb. The stem torque traces for the same five cold tests show consistent performance with no variation among tests. Figure 13 is a plot of the stem/stem-nut coefficient of friction for the same five cold tests. The data show consistent performance, with values at about 0.12 at the end of the stroke.

Figure 14 shows the stem thrust traces for the five hot tests. The five strokes show essentially the same profile as the cold tests, except that the final force at the end of the stroke has dropped from approximately 24,000 lb to approximately 20,000 lb. The torque traces for the same five hot tests are shown in Figure 15. Note how the running torque is higher with each successive stroke, even while the stem thrust remained constant among strokes. Note also how the final torque in the hot tests has the same value as in the cold tests. Both the increase in stem torque during running and the decrease in final stem thrust are an indication of an increase in the stem/stem-nut coefficient of friction. The increase in the friction associated with these tests is shown in Figure 16. The coefficient of friction started out significantly higher than in the cold tests (0.14 compared to 0.12) and continued to increase with each stroke at 250°F. A coefficient of friction as high as 0.20 was observed in the final hot test.

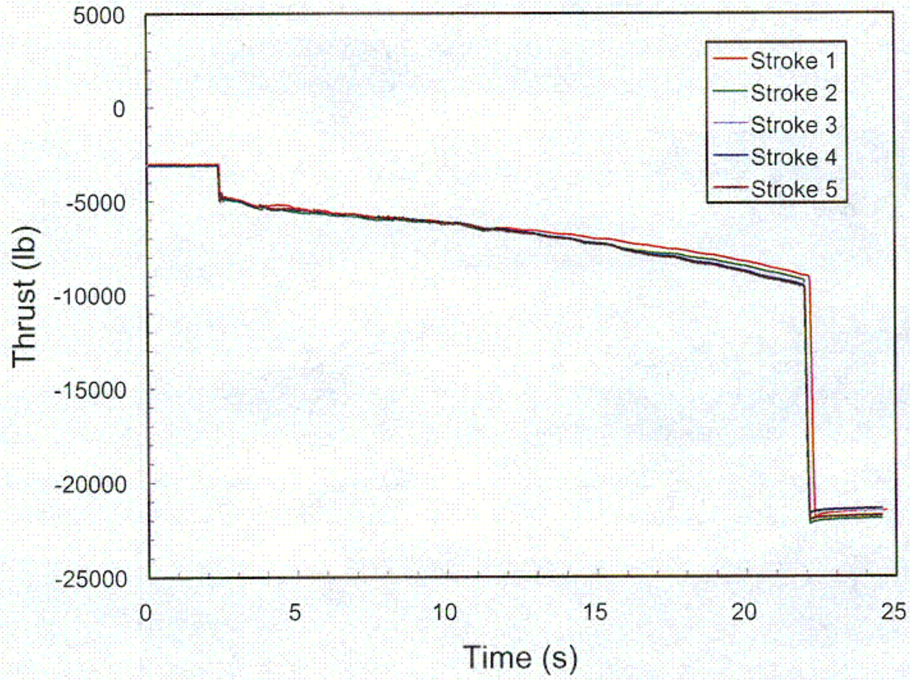

Figure 11. The five cold baseline tests for stem 2 with SRI show no variation in stem thrust between strokes.

C03

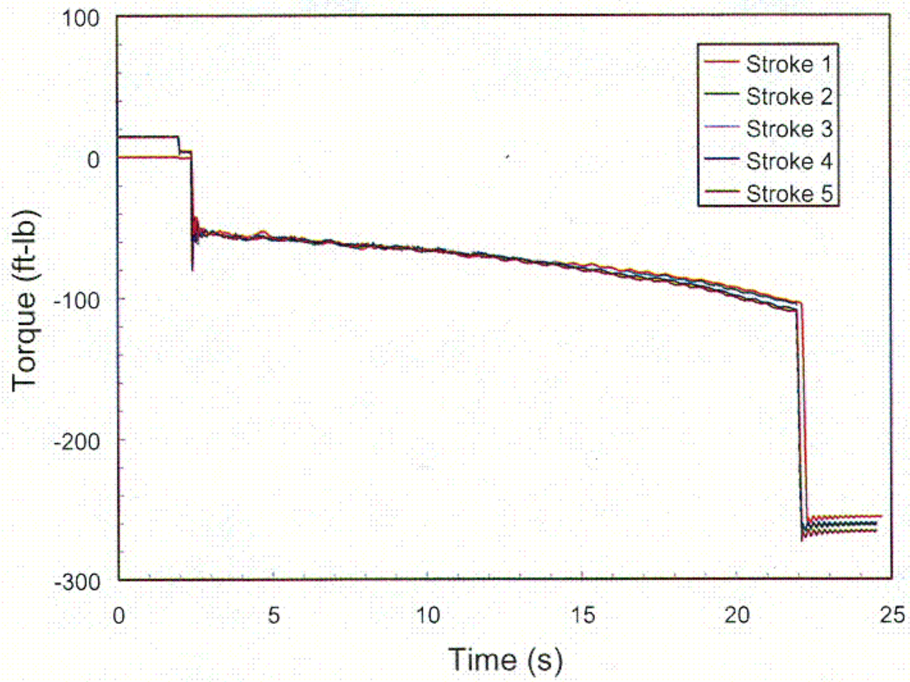

Figure 12. The five cold baseline tests for stem 2 with SRI show no variation in stem torque between strokes.

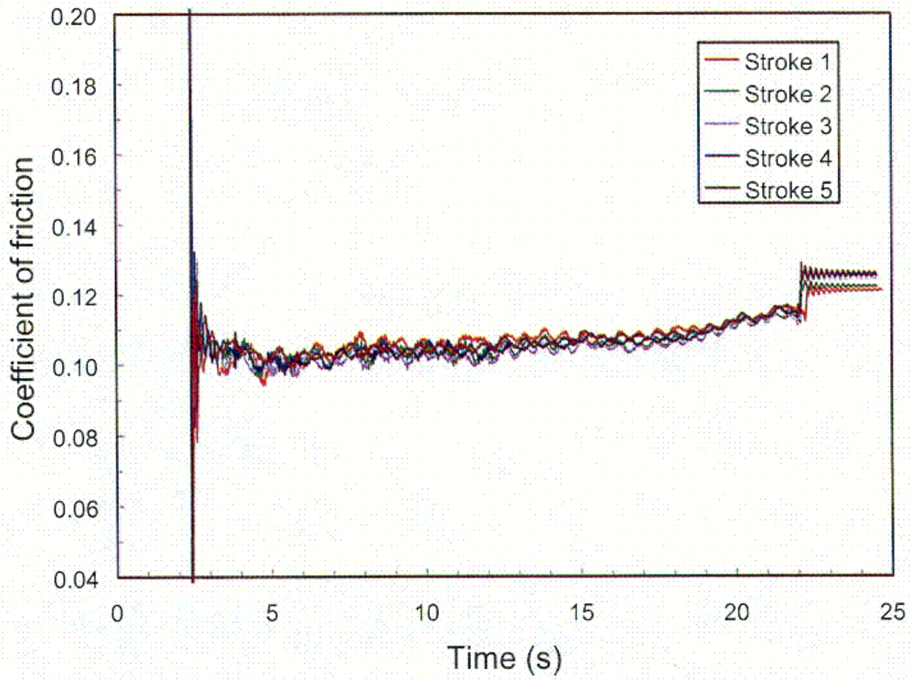

Figure 13. The five cold baseline tests for stem 2 with SRI show no variation in stem coefficient of friction.

C04

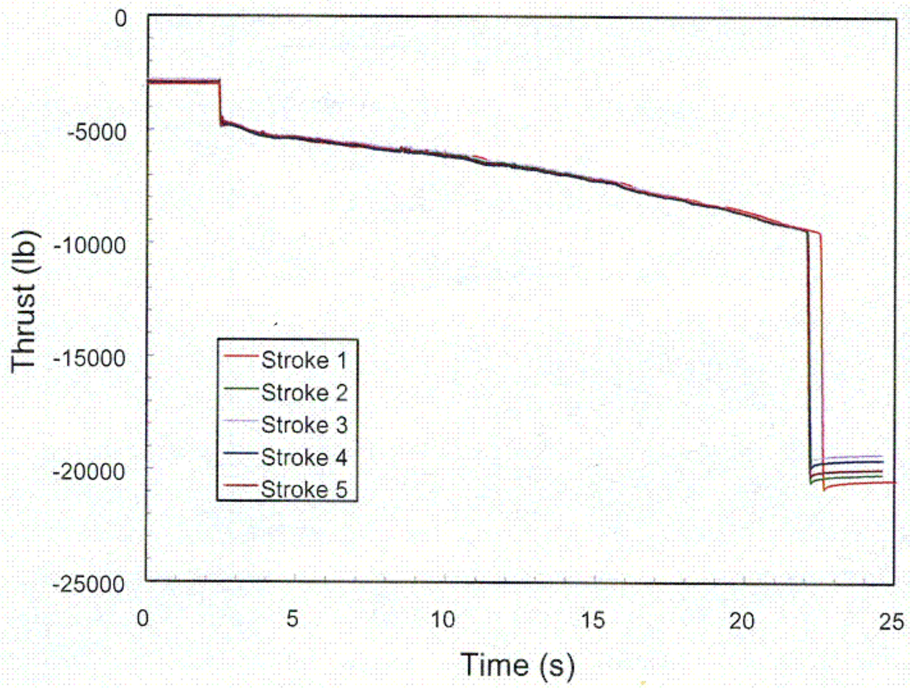

Figure 14. The five hot baseline tests for stem 2 with SRI show no variation in stem thrust between strokes.

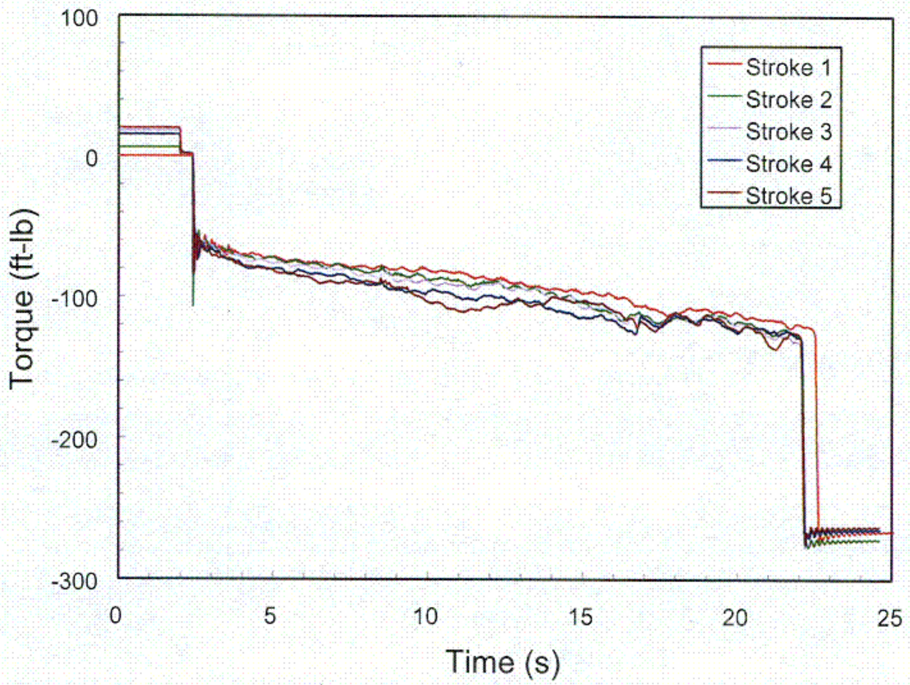

Figure 15. The five hot baseline tests for stem 2 with SRI show an increase in stem torque with each stroke.

C05

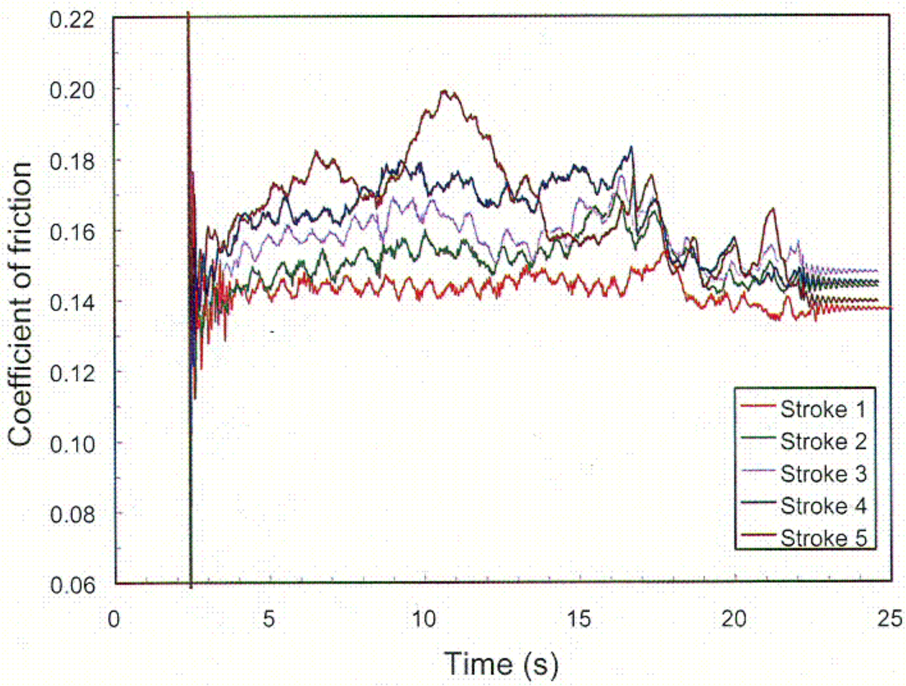

Figure 16. The five hot baseline tests for stem 2 with SRI show significant increase in stem friction.

Following the hot tests, the test stand was allowed to cool down to 70°F and another set of cold tests were performed. Figures 17, 18, and 19 show the stem thrust, stem torque, and stem/stem-nut coefficient of friction traces for these final cold strokes. The data in Figure 19 show that the coefficient of friction was lower for the first test and essentially the same as the earlier cold tests, while the other four were very consistent but higher.

To summarize, at room temperature the tests showed that the stem nut friction was very stable, similar in value to that in the earlier testing with other lubricants (documented in NUREG/CR-6100). At 250°F, the friction increases with the first stroke and continues to increase with each subsequent stroke. After cooling, the friction in the first subsequent cold test was similar to that in the earlier cold tests, while the friction in the other four strokes was relatively stable but slightly higher.

C06

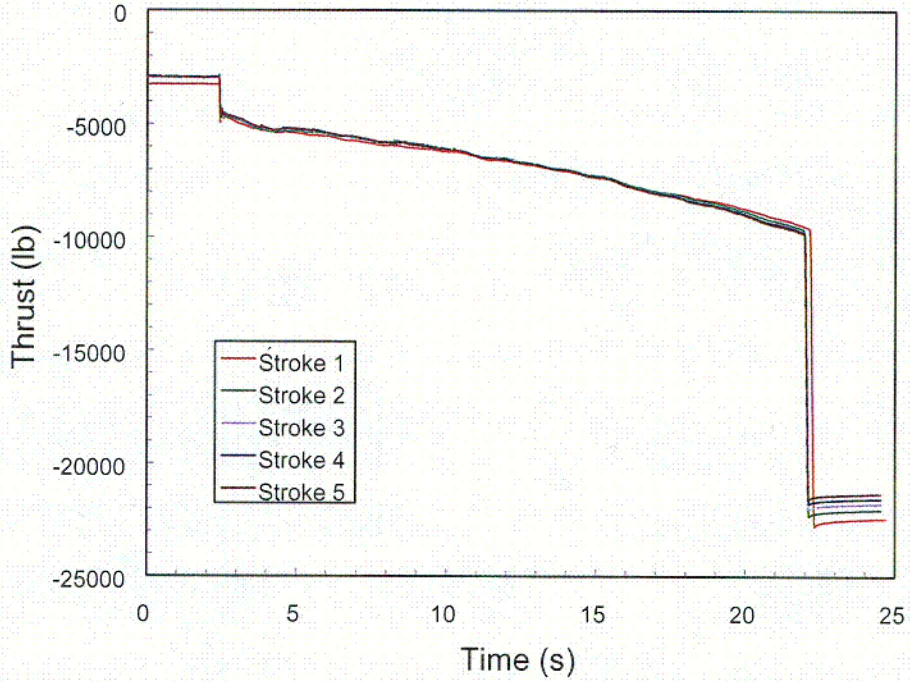

Figure 17. The five final cold tests for stem 2 with SRI show little variation in stem thrust between strokes.

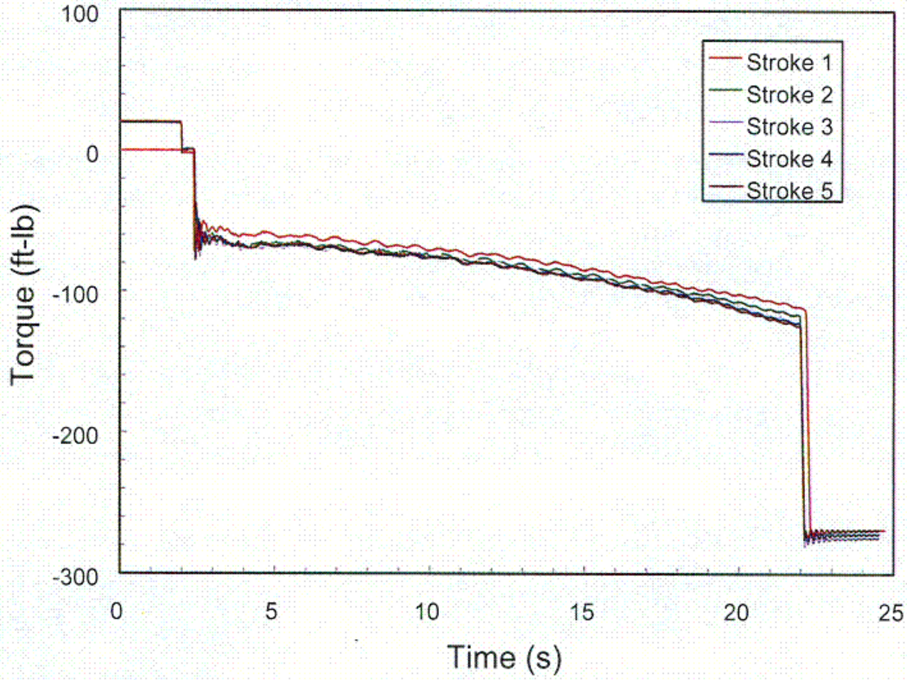

Figure 18. The five final cold tests for stem 2 with SRI show a small variation in stem torque between strokes.

C07

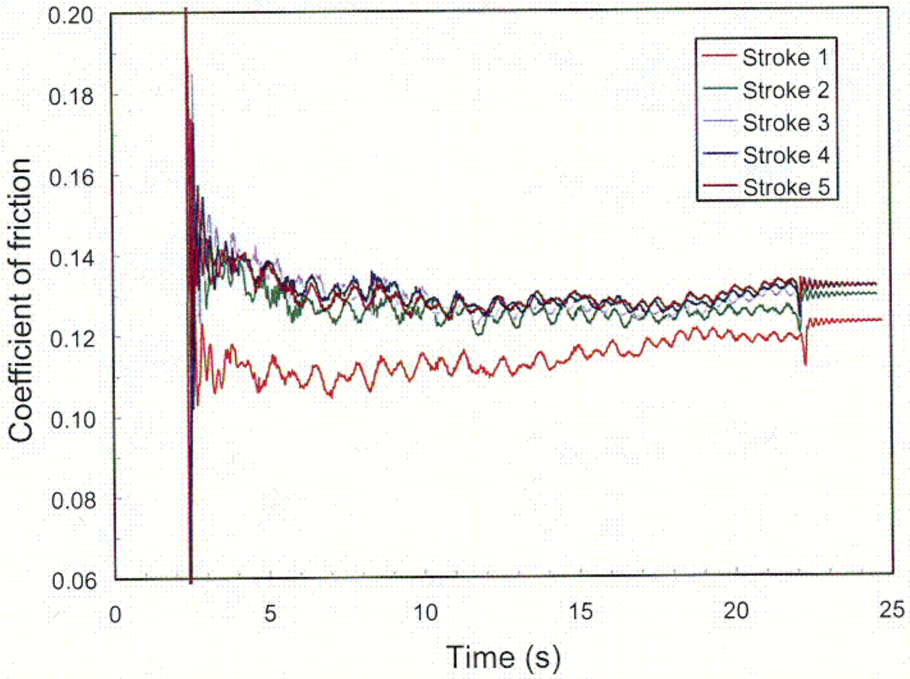

Figure 19. The five cold tests for stem 2 with SRI show a significant variation in stem friction after the first stroke.

C08

4.2. Elevated Temperature Tests

The purpose of the elevated temperature tests is to evaluate the change in stem/stem-nut coefficient of friction as the ambient temperature changes from normal in-plant temperatures to design-basis temperatures. The test series consisted of two strategies:

- Single-step design-basis tests, where the temperature was taken from 70°F directly to 250°F and then back to 70°F.

- Temperature step tests, where the temperature was increased from 70°F in three steps, typically 130, 190, and 250°F, then returned to 70°F at the conclusion of testing.

It is very important to understand how performance characteristics might change due to periodic valve cycling, changes from static to design basis conditions, and valve and lubricant aging. It is important to know if performance characteristics measured during a test can be considered typical of subsequent MOV performance, specifically design basis operation. Measured values for stem/stem-nut coefficient of friction are key factors in setting torque switches to appropriate levels. Increases in this value decrease the thrust available to overcome design basis loads, while decreases in this value increase final thrust, with the possibility of overloading valve and actuator structural components.

Our analysis of the elevated temperature tests will look at the performance of each grease using data from all four stem and stem nut combinations. We will include physical observations, consistency in performance among strokes, change with temperature, and change in ESFB. This analysis will be followed by an evaluation of the characteristic performance of each stem and stem nut combination using data from the five lubricants used. The following discussion addresses each of these topics.

4.2.1. Physical Observations

A number of photographs were taken to document the testing and the physical condition of the lubricants during the testing. These photographs are included in Appendix A of this report. The following paragraphs provide general observations made during the testing and documented in these photographs.

Exxon Nebula EP1

We used new EP1 for these tests, rather than the old lubricant (shelf aged approximately 10 years) that had been in storage. As mentioned earlier, the old EP1 was the supply that provided the sample used in the earlier accelerated aging tests. With this grease and with the other greases, we applied a thick layer of the grease to the stem and then rotated the stem nut about the stem by hand to produce a thin uniform layer. A small bead of lubricant was allowed to remain on each end of the stem nut to ensure adequate supply was present to allow the stem to re-lubricate itself during valve strokes. (This is consistent with typical industry practices for stem lubrication.) After the testing was completed, the stem and stem nut were removed and the lubricant was inspected.

As a result of the testing, the Nebula EP1 lubricant had changed from a light tan color to brown and appeared to have hardened inside the stem nut. The grease returned to its original consistency by gently working the grease (rubbing a sample between our fingers). The test results show no change in the lubrication characteristics of this grease as a result of the testing.

Chevron SRI

As a result of the elevated temperature testing, the Chevron SRI grease changed from the original green to dark brown. The lubricant bead above the stem nut and on the stem threads not worked during testing appeared to have hardened. The smear comparison, before and after testing, showed a change in color and consistency. A few days later, the oils in the grease had absorbed into the paper, approximately the same for each sample, indicating that the oil content remained consistent through the heat up and cool down.

Mobil Mobilgrease 28

The Mobil Mobilgrease 28 changed from a bright red color to almost black. Here again, the lubricant bead above the stem nut and on the stem threads not worked during the testing appeared to have thickened and hardened. The smear comparison, before and after testing, showed a change in color and consistency. A few days later, the absorption into the paper identified a changed after elevated temperature testing. The radius of absorption for the heated grease was about one half of that for the untested grease. The color of the oils being absorbed into the paper had also changed.

SWEPCO Moly 101

The SWEPCO Moly 101 did not appear to change as a result of the elevated temperature testing. A slight thickening of the grease was observed in the stem threads above and below the normal travel of the stem through the stem nut. We observed no difference in the before and after smear sample color, consistency, or absorption into the paper. No difference in the two samples was evident.

LOCTITE N-5000 Anti-Seize

The LOCTITE N-5000 anti-seize was also applied to the valve stem in an even, thin coat. After testing, the anti-seize had moved away from the threaded area, running down the stem. The N-5000 also separated, with the silver component running down the stem in a separate stream from the clear component. A very clear difference was observed in the lubrication layer on the bottom of the stem, which is the section being cycled during the test, and the layer on the top of the stem that had not been worked. Above the stem nut, the N-5000 looked the same as it did when it was originally applied. The anti-seize had also dripped from the stem nut onto the torque arm, again showing separation of the clear and silver components. This separation was clearly shown in the smear test.

4.2.2. Consistency Among Strokes

As shown previously in Figures 16 and 19, there can be a large variation in the stem nut coefficient of friction between strokes and even within the running portion of a single valve stroke. In order to make a consistent evaluation of the effects of different stems, lubricants, and temperatures on the friction coefficient, we chose to make this evaluation based on the performance observed at the end of the valve stroke, just prior to full seat contact. For a gate valve, this position is sometimes referred to as "at wedging." This analysis will take a single value for the stem nut coefficient of friction calculated from the average stem thrust and average stem torque based on the 200 data points (about 1/3 second) just prior to full seat contact. This position in a valve's closure stroke produces the highest loads during closure and is consistent with other analysis performed in the past. This portion of the MOVLS stroke also produces the highest stem loads. The figures discussed in the following sections will contain groups of five of these average stem nut friction values, one for each of the five valve strokes run at each test temperature.

Exxon Nebula EP1

Figure 20 contains the stem-nut coefficient of friction performance for the single step tests (70˚F to 250˚F and then back to 70˚F) and includes data for each of the four stems tested. For both Stem 2 and Stem 3, the initial cold test data show a lower stem nut friction (4% and 8% respectively) in the first stroke than in subsequent strokes. The other four strokes operated at essentially the same stem nut friction value. This low first stroke characteristic did not appear on the hot tests (middle data sets); however, Stem 2 appeared to have greater scatter among the hot strokes. The Stem 2 coefficient of friction increased for the final cold tests while Stem 3 returned to earlier cold performance, repeating the lower first stroke behavior. Stem 5 exhibited behavior similar to that of Stem 3.

Stem 4 is also shown in Figure 20 and shows very unique behavior. The coefficient of friction for the initial cold test starts very low at 0.086 and increases with each stroke to 0.124. The hot tests are stable, showing no increasing with stroke but running at values similar to the fifth stroke of the initial cold test. The final cold tests begin at the hot test value and increase dramatically with each stroke, ending at a very high value of 0.159.

Figure 21 shows similar data for the incremental temperature step tests (70˚F to 130˚F to 190˚F to 250˚F and then back to 70˚F). The performance of each of the four stems is similar to that shown in Figure 20. Stem 4 continues to exhibit large increases in stem nut coefficient of friction in the cold tests, but stable values in the each hot test. Similarly, Stem 2 shows greater scatter in the hot tests.

Chevron SRI

The Chevron SRI cold baseline test shows good repeatability among the five strokes, as shown in Figure 22. As the temperatures increase, more variability is evident among the five strokes, with the first being the lowest and increasing with each additional stroke. This trend reverses after cool down, where the first stroke can be 5 to 10% higher.

As with the Nebula EP1, Stem 2 with Chevron SRI has more scatter between tests at high temperature. Figure 22 contains two data sets for Stem 2, the first being the aging test series (shown earlier in Section 4.1.2) and the second being the single step elevated temperature test. During the 250˚F tests, the Stem 2 coefficient of friction was basically the same for the first three strokes. In the aging test, the coefficient of friction decreased for the forth and fifth strokes. The coefficient of friction continued to increase rapidly in the single step elevated temperature test, eventually reaching a value of 0.195. Stem 2 immediately returned to earlier cold baseline performance upon cool down.

Figure 23 shows data for the incremental temperature step tests with Chevron SRI. The performance of all four stems is similar to that shown in Figure 22. The data shows good repeatability among each set of five strokes and more variability at elevated temperature. The coefficient of friction increases with each stroke at 130˚F and 190˚F. At 250˚F, Stem 5 continues to increase with each stroke, but Stems 3 and 4 exhibit a higher first stroke with stable and slightly lower values for the second through the fifth strokes. Once again, the trend reverses after cool down, where the first stroke was 5% to 10% higher.

Figure 23 also includes two tests for Stem 2, one at a low torque switch setting (LTS) and one at a high torque switch setting (HTS). These two tests also closed against different running stem thrusts. The performance of Stem 2 with Chevron SRI was very repeatable between the two tests, especially at cold and maximum temperature conditions.

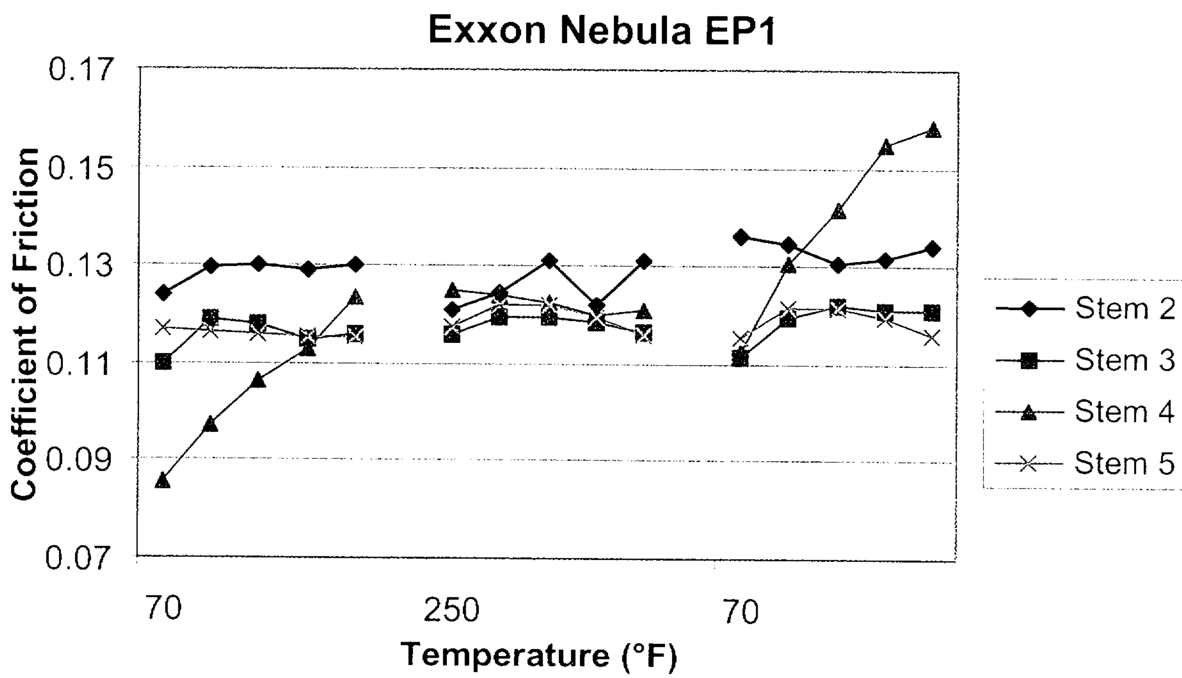

Figure 20. Stem nut coefficient of friction for each stroke of the single step tests with EP1.

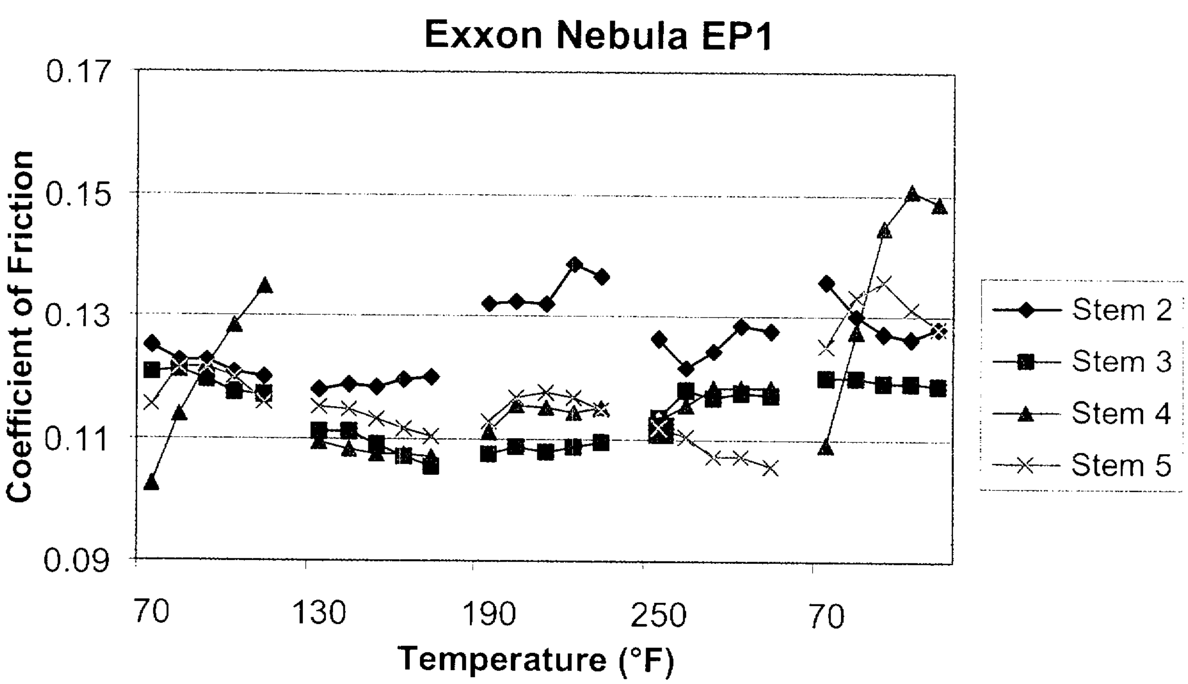

Figure 21. Stem nut coefficient of friction for each stroke of the multiple step tests with EP1.

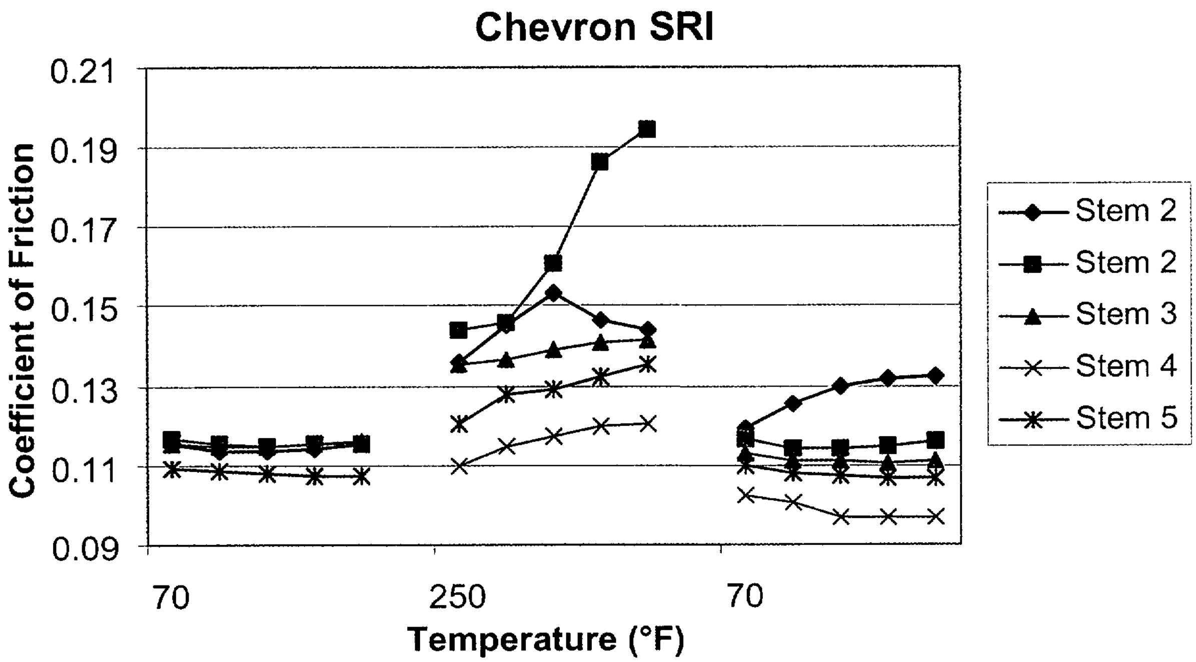

Figure 22. Stem nut coefficient of friction for each stroke of the single step tests with SRI.

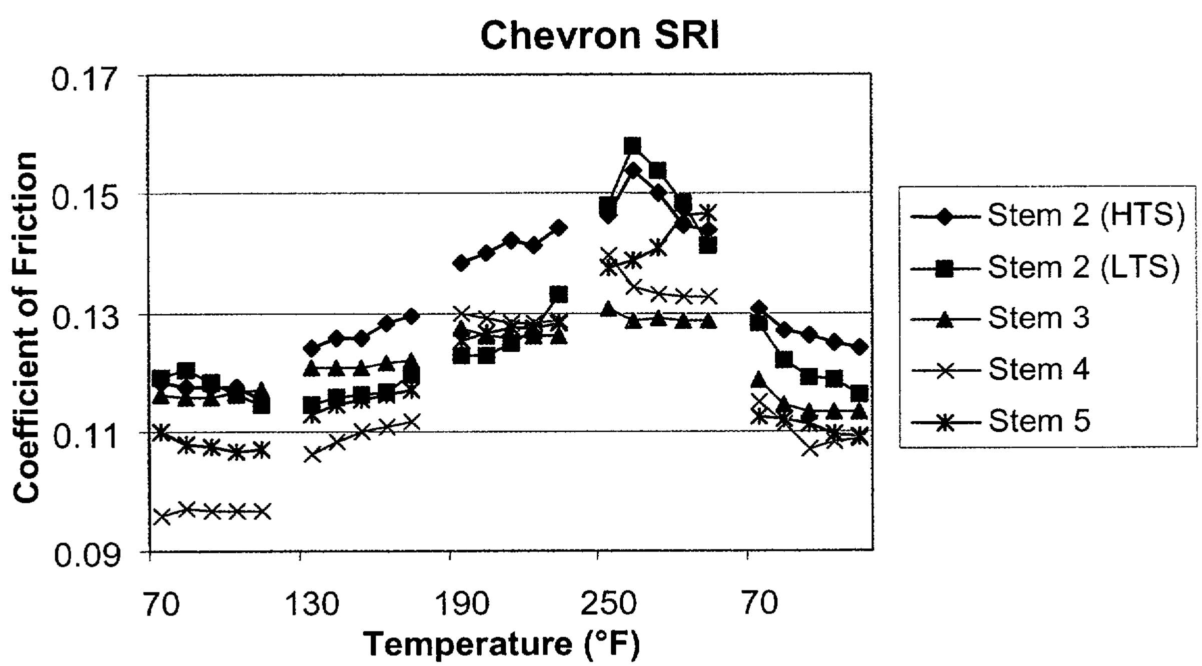

Figure 23. Stem nut coefficient of friction for each stroke of the multiple step tests with SRI.

Mobil Mobilgrease 28

The Mobil Mobilgrease 28 cold baseline test shows good repeatability among the five strokes, as shown in Figure 24, with the exception of the first test series using Stem 4. The first cold baseline tests with Stem 4 and Mobilgrease 28 saw a significant increase in the stem nut coefficient of friction over the five strokes; however, we also observed that the actual values were extremely low (running from 0.03 to 0.05). Because the values were so low, the tests were repeated with a new coating of the Mobilgrease. This second set of tests (identified as Stem 4B) performed similarly to the other stems and the increase observed earlier had disappeared.

Once again, Stem 2 has more scatter between tests at high temperature. Figure 24 shows that the stem nut coefficient of friction for Stem 2 at 250°F exhibits wide and random variations between 0.128 and 0.144. All stems show good repeatability during the final cold tests.

Figure 25 shows data for the incremental temperature step tests with Mobilgrease 28. Once again, we see the first cold baseline tests beginning at very low values for the stem nut coefficient of friction, while the second cold baseline tests closer to that observed for the other stems. Figure 25 also shows that Stem 2 is very repeatable until the 190°F test. For both the 190°F and the 250°F tests, Stem 2 exhibits a low first stroke followed by large increases. Stem 5 also shows this behavior, but less pronounced. Stem nut friction coefficients for Stem 2 and 5 drop back down to more normal values during the forth and fifth strokes.

SWEPCO Moly 101

Figure 26 contains the stem-nut coefficient of friction performance for the single step tests for SWEPCO Moly 101. Stems 2, 3, and 5 show very good repeatability over the five initial cold strokes, but Stem 4 begins very low and increases with each stroke, from 0.075 to 0.099. At 250°F, Stem 4 becomes stable over five strokes but Stems 2 and 5 show wide variations, 0.149 to 0.173 and 0.141 to 0.180 respectively. In the final cold tests, all four stems returned to earlier cold performance, repeating the lower first stroke behavior. Stem 4 exhibited a slight increase with each of the five strokes, but much less variation than in the initial cold tests.

Figure 27 shows similar data for the incremental temperature step tests. The performance of each of the four stems is similar to that shown in Figure 26, except that the Stem 4 strokes began at a higher stem nut coefficient of friction and were stable during the five initial cold strokes. Note that there are no data points show in Figure 27 for Stem 3 at 250°F. We experienced a heater failure during the heatup period from 190° F to 250°F and the higher temperature was never reached. Also, the data shown for Stem 2 at 130°F was actually taken at 145°F because the heater controller was set improperly.

Stem 2 experienced an apparent breakdown in lubrication during the 190°F and the 250°F tests. The stem nut coefficient of friction data show an increase with each stroke beginning at 0.138 in the 190°F stroke and increasing to 0.190 in the final 250°F stroke. This is similar to the performance of both Stem 5 and even Stem 2 in the single step tests.

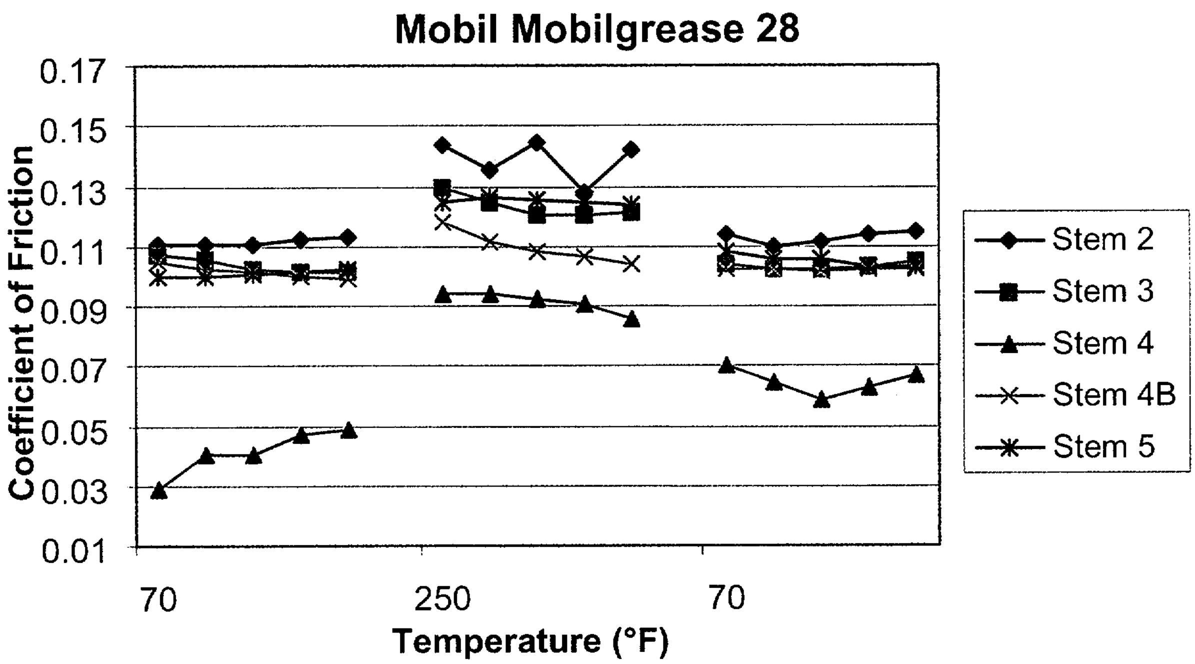

Figure 24. Stem nut coefficient of friction for each stroke of the single step tests with Mobil 28.

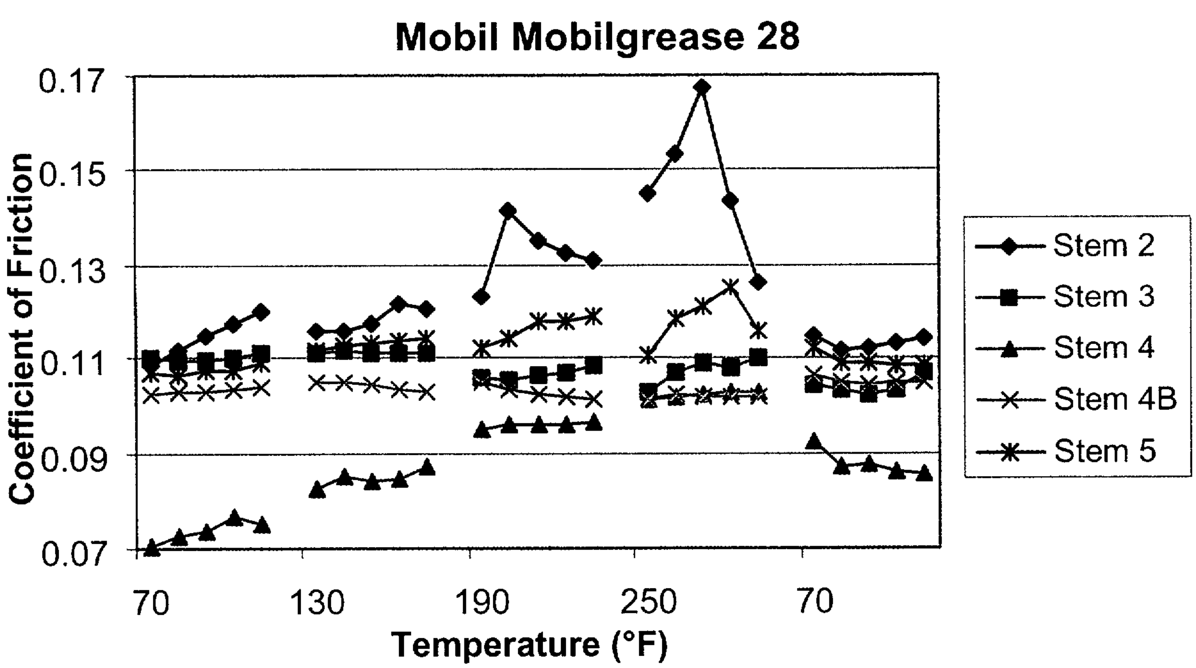

Figure 25. Stem nut coefficient of friction for each stroke of the multiple step tests with Mobil 28.

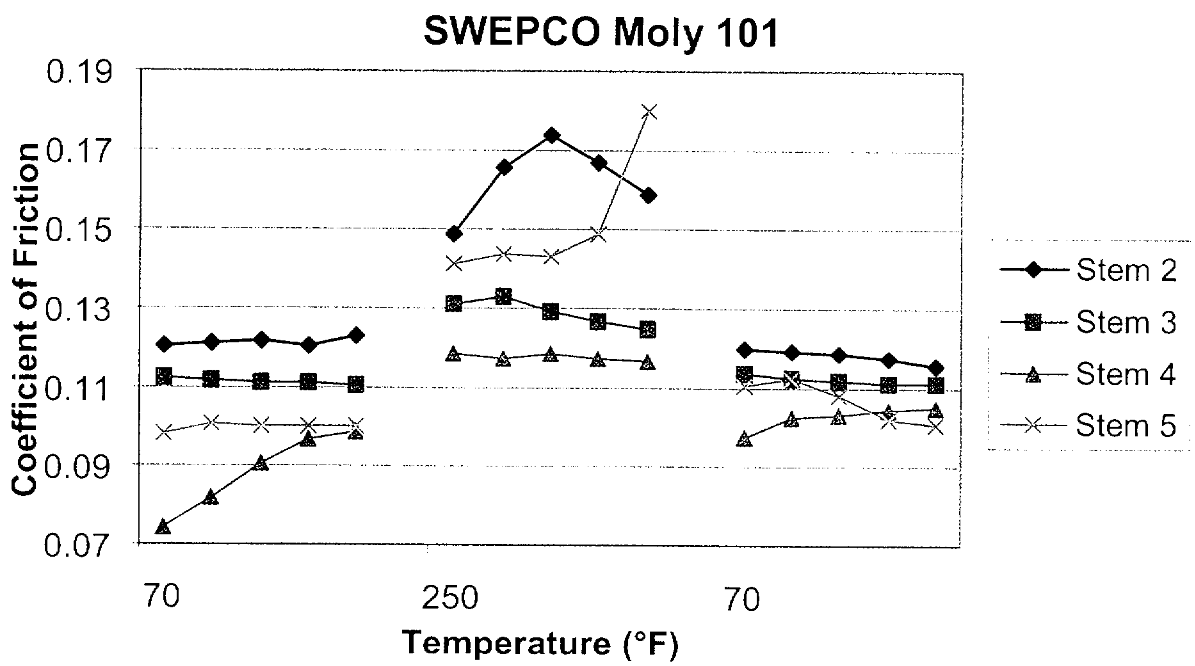

Figure 26. Stem nut coefficient of friction for each stroke of the single step tests with Moly 101.

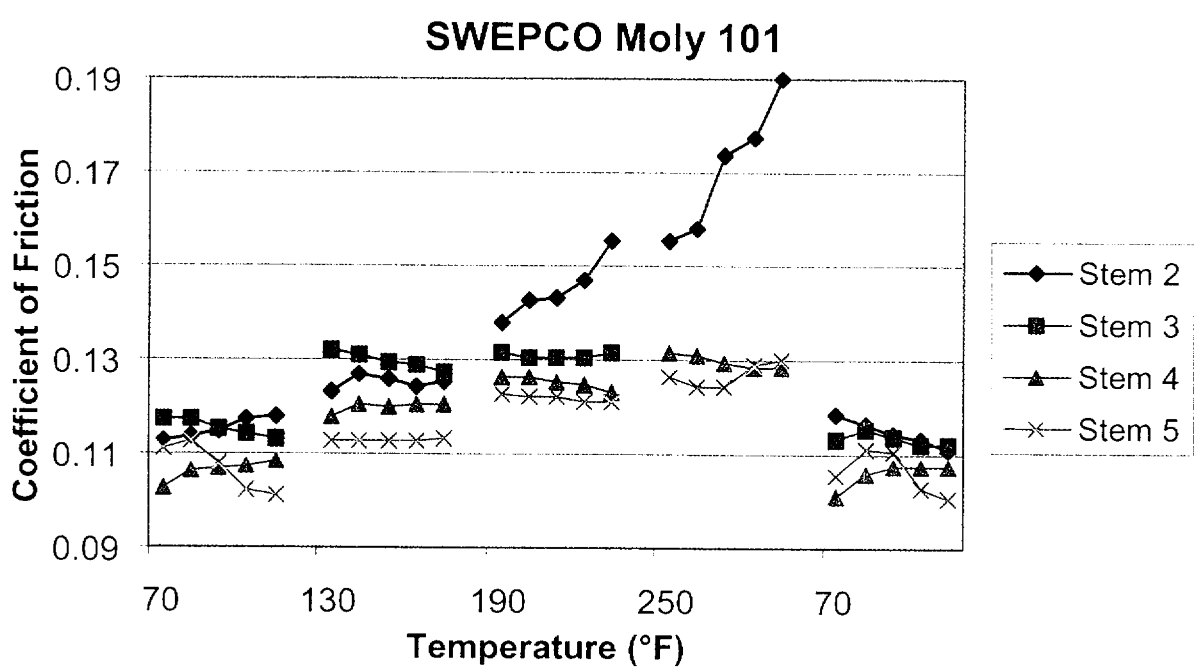

Figure 27. Stem nut coefficient of friction for each stroke of the multiple step tests with Moly 101.

LOCTITE N-5000 Anti-Seize

The LOCTITE N-5000 Anti-Seize cold baseline tests show large variations among the five strokes, as shown in Figure 28. As the temperatures increase, more variability is evident among the five strokes for some stems (Stem 3 and Stem 5) but others show more stability (Stem 2 and Stem 4). After cooldown, the performance of each stem is similar to its cold baseline performance.

Once again, Stem 4 exhibits unique behavior. In both the initial cold baseline test and the final cold test, the stem nut coefficient of friction increases dramatically from the first stroke to the second stroke. From the first stroke to the second stroke in the final cold test, the coefficient of friction increased from 0.138 to 0.183 or a 33% increase. Values continue to increase with the third stroke to very high values (0.191 in the third final cold stroke) then decrease with the forth and fifth strokes.

Figure 29 shows data for the incremental temperature step tests with LOCTITE N-5000. The performance of all four stems is similar to that shown in Figure 28. The data show large variations among the five strokes for many tests. Often the first stroke is very low when compared with subsequent strokes, as seen in the Stem 5 data and several tests with Stems 3 and 4. In contrast, the Stem 2 coefficient of friction begins high in many cases, as does Stem 3 in the 130°F test.

4.2.3. Change With Temperature

The figures in the preceding section of this report also provide insights into the overall effect that elevated temperature has on each stem and lubricant. However, the variations from stroke to stroke for each test sometimes makes it difficult to clearly see the real temperature effect. This section of the report provides an evaluation of the relationship between temperature and stem nut coefficient of friction using single values for each test. The single values are obtained by simply averaging each set of five strokes from Figures 20 through 29. The figures found in the following discussion show this average stem nut coefficient of friction plotted as a function of temperature for Stem 2. The figures also include a linear fit through those data points to help visualize the relationship. These figures are typical of the performance of the full data set of four stems and five lubricants. Appendix B of this report contains a complete set of figures covering all stems and lubricants tested.

Table 4 provides a summary of this analysis and provides the 70°F and 250°F coefficient of friction values based on this linear fit. It also provides the percent change over the same temperature range. The negative values for percent change for all stems with the Nebula EP1 and for Stems 3 and 4 with the N-5000 indicate cases where the stem nut coefficient of friction decreased at elevated temperatures.

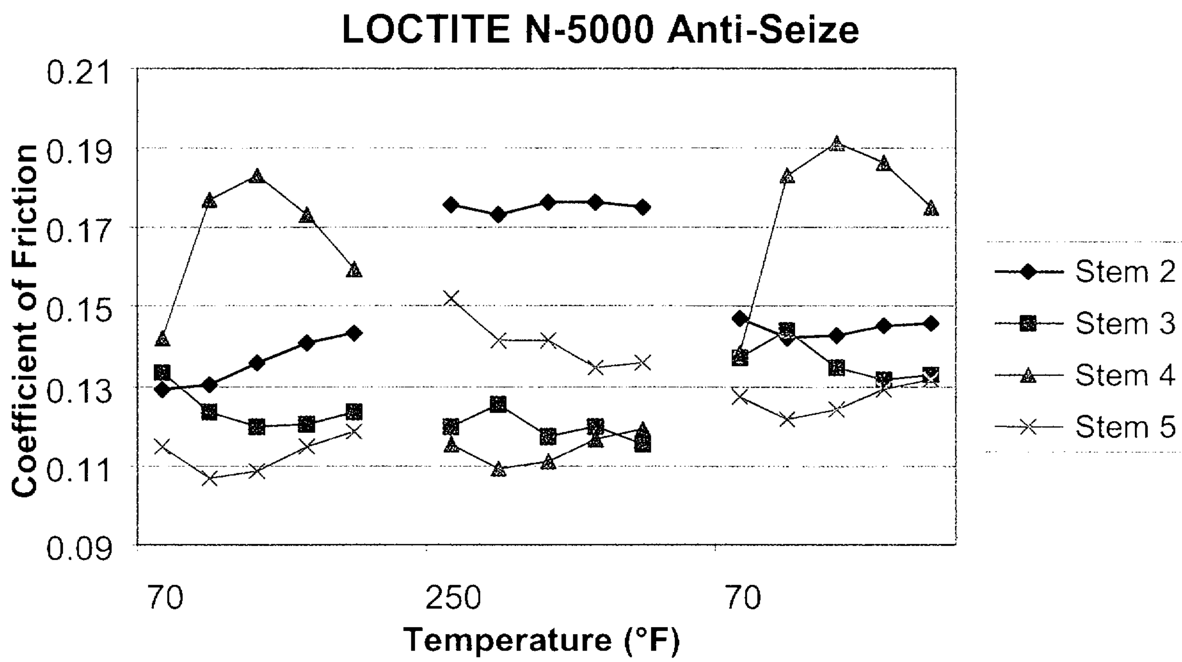

Figure 28. Stem nut coefficient of friction for each stroke of the single step tests with N-5000.

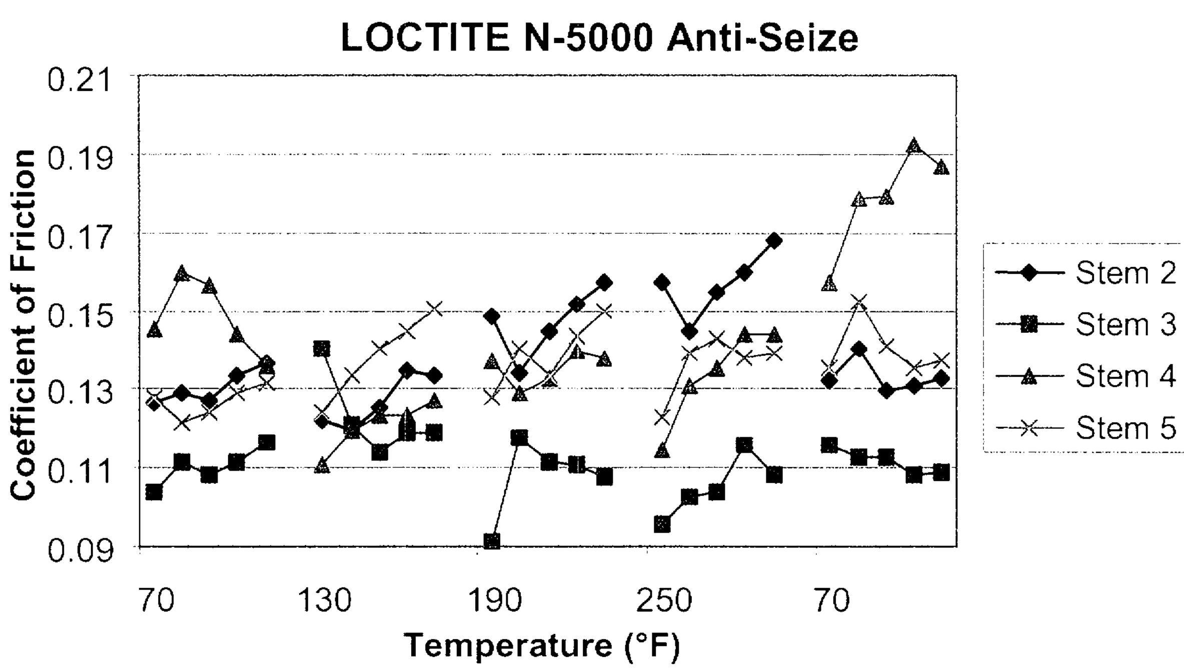

Figure 29. Stem nut coefficient of friction for each stroke of the multiple step tests with N-5000.

Table 4. Change in stem/stem-nut coefficient of friction with temperature.

		Exxon Nebula EP1	Chevron SRI	Mobil Mobilgrease 28	SWEPCO Moly 101	LOCTITE N-5000
Stem 2	**Stem μ - 70°F**	0.128	0.118	0.112	0.116	0.133
	Stem μ - 250°F	0.127	0.149	0.142	0.164	0.162
	Percent Δμ	-0.6%	26.6%	26.8%	41.6%	21.9%
Stem 3	**Stem μ - 70°F**	0.105	0.103	0.097	0.103	0.111
	Stem μ - 250°F	0.102	0.120	0.100	0.120	0.099
	Percent Δμ	-2.8%	16.5%	3.1%	16.5%	-10.8%
Stem 4	**Stem μ - 70°F**	0.123	0.098	0.085	0.102	0.163
	Stem μ - 250°F	0.116	0.129	0.103	0.127	0.120
	Percent Δμ	-5.9%	32.1%	19.3%	24.7%	-35.4%
Stem 5	**Stem μ - 70°F**	0.120	0.109	0.106	0.103	0.128
	Stem μ - 250°F	0.113	0.135	0.122	0.137	0.140
	Percent Δμ	-7.2%	24.7%	15.0%	32.7%	9.4%

Exxon Nebula EP1

In the previous accelerated aging tests with the old EP1, we saw very large increases in the stem/stem-nut coefficient of friction. This appears to be entirely related to the age of the grease because our testing with the new EP1 grease experienced essentially no change due to elevated temperature. An overview of the data shown previously in Figures 20 and 21 show no general increase in stem nut friction at elevated temperature. Figure 30 shows the relationship between temperature and stem nut coefficient of friction using single values for each test of Stem 2 with Nebula EP1. The linear fit through the data points indicates a decrease in stem nut friction as temperatures increase. This was also true for Stems 3, 4, and 5 as well, as seen in Table 4. Recall from the previous section that the Nebula EP1 grease was also more stable with less data scatter and less influence of multiple strokes at elevated temperature than it was at cold conditions.

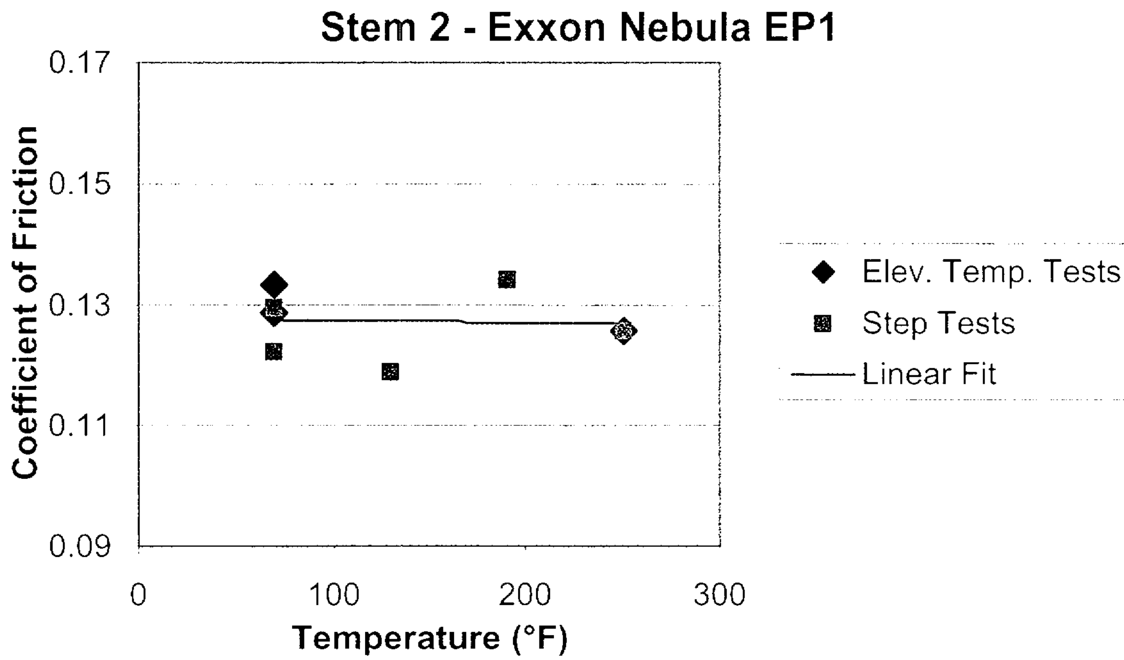

Figure 30. Typical flat or decreasing change in stem nut friction at elevated temperature.

Chevron SRI

The data shown previously in Figures 22 and 23 indicated that temperature has a strong influence on stem nut friction for Chevron SRI. Figure 31 shows this increase for Stem 2. The linear fit through the data points shows a significant increase from 70° F to 250°F of 26.6% for Stem 2. Stem 4 saw the largest increase at 32.1%.

Mobil Mobilgrease 28

Figures 24 and 25 show that elevated temperature has a strong influence on the stem nut coefficient of friction for the Mobilgrease 28 for some stems and under some conditions. All stems show increases in friction during the single step tests. But during incremental step tests, Stem 2, the first Stem 4, and Stem 5 have increasing coefficients of friction. (Recall that Stem 4 testing was repeated due to the unusual performance in the first test series.) Stem 3 and the second Stem 4 show essentially no change with temperature. Stem 2 saw the largest increase with Mobilgrease 28, increasing 26.8% from 70 to 250°F.

SWEPCO Moly 101

The data shown previously in Figures 26 and 27 show that the SWEPCO Moly 101 has a strong stem nut coefficient of friction increase with temperature for all stems tested. The linear fit through the data points shows a significant increase from 70° F to 250°F for Stem 2 of 41.6%. Stems 5, 4, and 3 followed at 32.7%, 24.7%, and 16.5% increase, respectively.

LOCTITE N-5000 Anti-Seize

The data in Figures 28 and 29 shows that temperature has a strong influence on the stem nut coefficient of friction for the LOCTITE N-5000 Anti-Seize for some stems and under some conditions.

Stem 2 and Stem 5 show increases in friction during the single step tests, but Stem 3 and Stem 4 show decreases. During incremental step tests, Stem 3 and Stem 5 coefficients of friction do not change with temperature, while Stem 2 increases as temperature increases and Stem 4 decreases. As shown in Figure 29, Stem 2 with the N-5000 Anti-Seize experienced a strong coefficient of friction increase from 70 to 250°F, but with large variations during intermediate temperature steps. The friction actually got lower with the first step to 130°F.

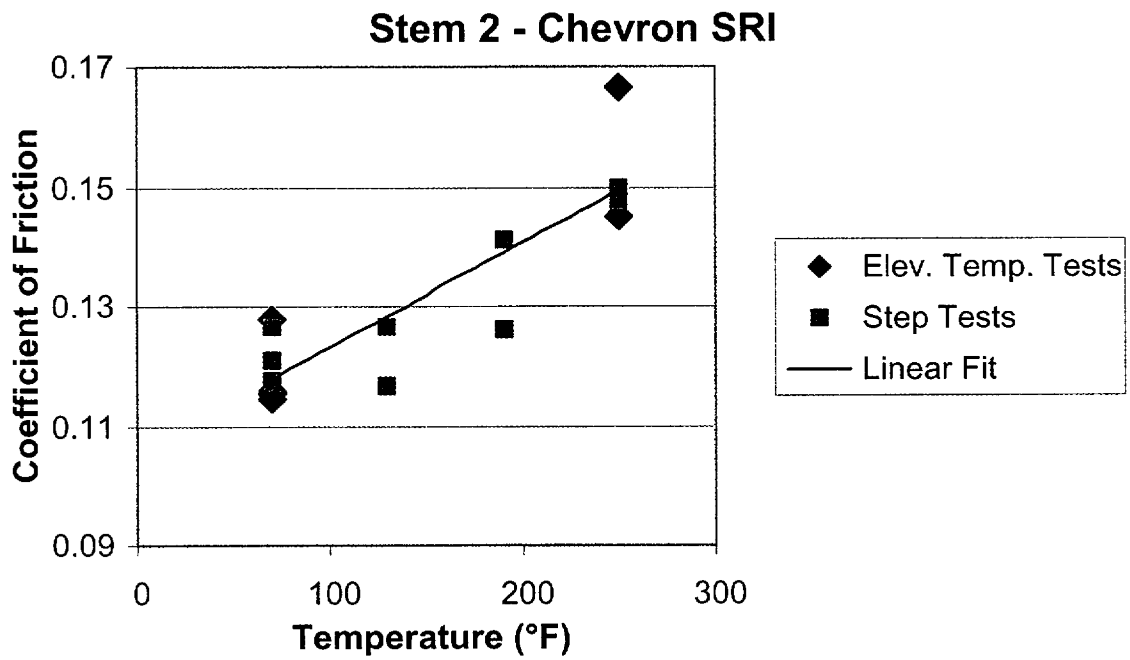

Figure 31. Typical increasing change in stem nut friction at elevated temperature.

4.2.4. Change In End Of Stroke Friction Behavior (ESFB)

As described earlier in this report, when closing an MOV, a significant change in the stem nut coefficient of friction can occur at the end of valve travel when seating or wedging occurs. Most often, the coefficient of friction drops to a very low value making the MOV performance at torque switch trip look overly optimistic. The difference between running and torque switch trip coefficients of friction has been called rate-of-loading or, describing the phenomena itself, load-sensitive behavior. Each individual stem/stem nut combination was found to be unique, with its own particular coefficient of friction profile. Some stems are more likely than others to exhibit load-sensitive behavior.

Figure 32 provides a typical stem force trace from high flow testing of a flexible-wedge gate valve. Note the positions marked as "Full seat contact", "Torque switch trip", and "Maximum force." A typical rate-of-loading analysis looks at the change in stem nut friction from full seat contact to torque switch trip. Our evaluation of the change in stem nut friction at the end of valve travel, will look at the total change from full seat contact to the final stem position, the maximum force point identified in Figure 32. To differentiate between this type of analysis and the more common rate-of-loading analysis, we shall refer to the MOV's end of stroke friction behavior (ESFB). In the following discussion we will compare the ESFB observed in the baseline cold tests with the ESFB observed at elevated conditions. This analysis

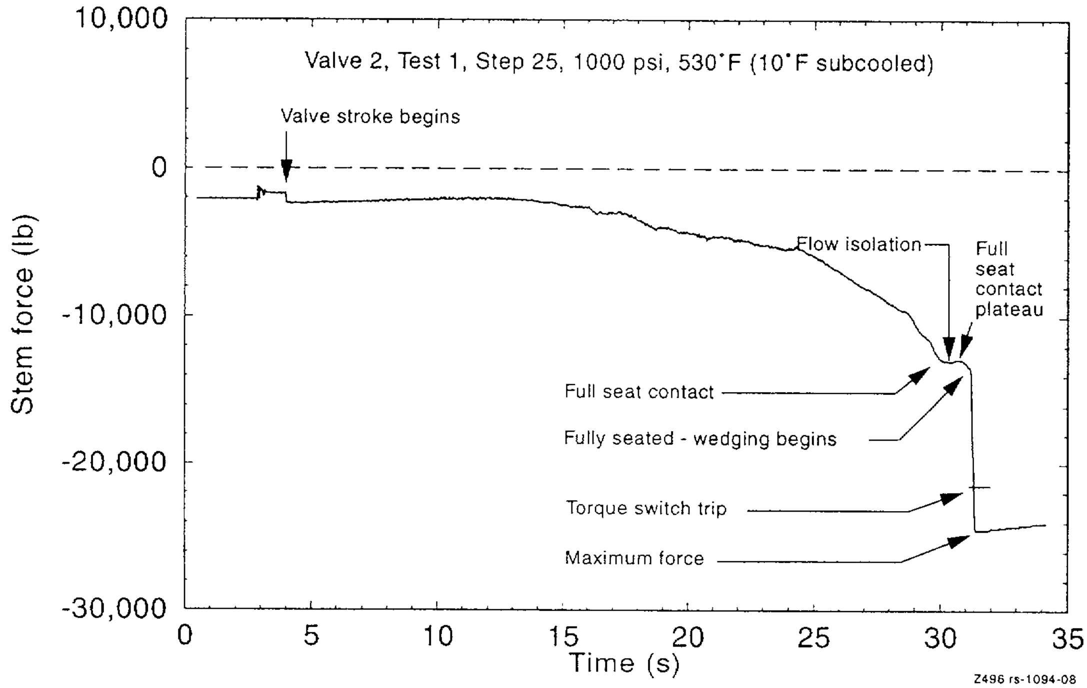

Figure 32. Data trace from a high flow closure test of a flexible-wedge gate valve.

will use a single value for the stem nut coefficient of friction, based on the last 200 data points (about 1/3 second) prior to full seat contact, and compare that to the average coefficient of friction based on the final loads (after torque switch trip).

A change in ESFB performance is not of great concern for closing an MOV since it occurs after the valve has seated. Recall that rate-of- loading or load-sensitive behavior deals with same phenomena but focuses on torque switch setting under low load, ambient temperature conditions. An increase in ESFB means lower stem nut friction at the end of stroke and higher final stem thrusts. This could challenge MOV structural limits and greatly increase the unwedging thrust required to open an MOV. A decrease in ESFB reduces the final stem thrust, but might also reduce the thrust available to unwedge the MOV in the opening direction.

Table 5 provides a summary of this analysis and provides the average ESFB for the single step elevated temperature tests. It also provides the ESFB as a percent change based on the coefficient of friction prior to full seat contact. Appendix C contains figures for each lubricant and each stem, where ESFB is plotted as a percent change from the final running load to the final seating load. The following paragraphs discuss the changes in ESFB due to elevated temperature for each lubricant.

Table 5. Change in end of stroke friction behavior (ESFB) with temperature.

		Exxon Nebula EP1		Chevron SRI		Mobil Mobilgrease 28		SWEPCO Moly 101		LOCTITE N-5000	
		ESFB	% ESFB	ESFB	% ESFB	ESFB	% ESFB	ESFB	% ESFB	ESFB	% ESFB
Stem 2	**Initial Cold, 70°F**	0.037	28%	-0.002	-2%	0.004	4%	0.009	7%	0.029	21%
	Hot Test, 250°F	0.021	17%	0.030	18%	0.039	28%	0.028	17%	0.009	5%
	Final Cold, 70°F	0.039	30%	0.004	4%	0.009	8%	0.006	5%	0.037	25%
Stem 3	**Initial Cold, 70°F**	0.056	51%	0.022	20%	0.018	17%	0.022	20%	0.042	34%
	Hot Test, 250°F	0.030	25%	0.017	12%	0.002	2%	0.011	9%	0.024	20%
	Final Cold, 70°F	0.062	52%	0.024	22%	0.022	21%	0.021	19%	0.051	38%
Stem 4	**Initial Cold, 70°F**	0.071	68%	0.056	71%	0.023	22%	0.073	83%	0.067	40%
	Hot Test, 250°F	0.062	51%	0.053	46%	0.017	15%	0.059	50%	0.026	23%
	Final Cold, 70°F	0.083	59%	0.061	62%	0.027	27%	0.075	73%	0.052	30%
Stem 5	**Initial Cold, 70°F**	0.036	31%	0.020	19%	0.032	32%	0.031	31%	0.023	20%
	Hot Test, 250°F	0.027	23%	0.009	7%	0.024	19%	0.028	19%	0.020	14%
	Final Cold, 70°F	0.037	31%	0.021	19%	0.033	32%	0.028	26%	0.021	16%

Exxon Nebula EP1

Each of the four stems exhibited a drop in the ESFB from the initial cold test to the hot test, and then a return to the higher value after cooldown. The stems with more extreme ESFB also show the largest change in ESFB with elevated temperature. Stem 4 had the highest ESFB, beginning at 68% meaning that the final friction was 68% lower than the running friction. At hot conditions, the ESFB dropped to 51%. Stem 3 was also high at a cold value of 51% and 25% hot. Stems 2 and 5 have lower initial ESFB at 28% and 31% respectively. At 250°F, the ESFB for Stems 2 and 5 drops to 17% and 23%, respectively.

Chevron SRI

The ESFB performance of the four stems is quite different with Chevron SRI. Once again Stem 4 is very high during the cold tests with 71% ESFB in the initial cold test and 62% in the final. The hot test ESFB drops to 46%. Stem 3 is no longer high but instead performs very close to Stem 5. The ESFB performance of both Stems 3 and 5 drops during the hot tests. Stem 2 exhibits ESFB performance where the temperature influence is reversed. Stem 2 begins with a slightly negative ESFB and increased with elevated temperature.

Mobil Mobilgrease 28

The ESFB performance of the four stems is once again unique when tested with the Mobilgrease 28 lubricant. Stem 4 no longer has the highest ESFB performance, dropping from 68% and 71% for Nebula EP1 and Chevron SRI to 22% in the initial cold tests. Stem 5 is now the highest stem at 32% and drops to 19% at elevated temperature. Stem 3 has also moved to a much lower position, beginning at 17% in the cold test an dropping to almost zero in the hot test.

Once again, Stem 2 exhibits ESFB performance where the temperature influence is reversed. Stem 2 begins with only 4% ESFB and increases dramatically to 28% with elevated temperature.

SWEPCO Moly 101

The performance of the four stems with Moly 101 is very similar to the performance of each stem with Chevron SRI except that Stem 5 is now a little higher than Stem 3. Once again Stem 4 is very high during the cold tests with 83% ESFB in the initial cold test and 73% in the final. The hot test ESFB drops to 50%. Stem 3 is no longer high but instead performs very close to Stem 5. The ESFB performance of both Stems 3 and 5 drops during the hot tests. Stem 2 exhibits ESFB performance where the temperature influence is reversed. Stem 2 begins with a low ESFB and increased with elevated temperature.

LOCTITE N-5000 Anti-Seize

The ESFB performance of the four stems is much more consistent when tested with the N-5000 Anti-Seize. Stem 4 no longer has extremely high ESFB performance, dropping values very similar to Stem 3. Stem 4 remains highest stem at 40% and drops to 23% at elevated temperature. Stem 3 exhibits similar performance, beginning at 34% in the cold test and dropping to 20% in the hot test.

Stem 5 shows little change in its ESFB. It ranges from 20% to 14% for the initial cold test and the hot test, and returns to 16% in the final cold test. The Stem 2 ESFB performance is no longer opposite to that of the other stems. It begins at 21% ESFB and drops to almost zero with elevated temperature.

4.2.5. Stem – Stem Nut Performance

In the previous analysis, we observed that each individual stem and stem nut combination appear to have unique characteristics with regard to the amount of variation between strokes, elevated temperature performance, and end of stroke friction behavior. This section will explore each individual stem and stem nut combination in a manner very similar to that used previously. Unique stem and stem nut performance characteristics will be identified.

Figure 33 shows a comparison between the stem thread slopes for each of the 4 stems. This information helps understand the differences between stems and why Stem 2 and Stem 5 appear to perform somewhat similarly as does Stems 3 and 4.

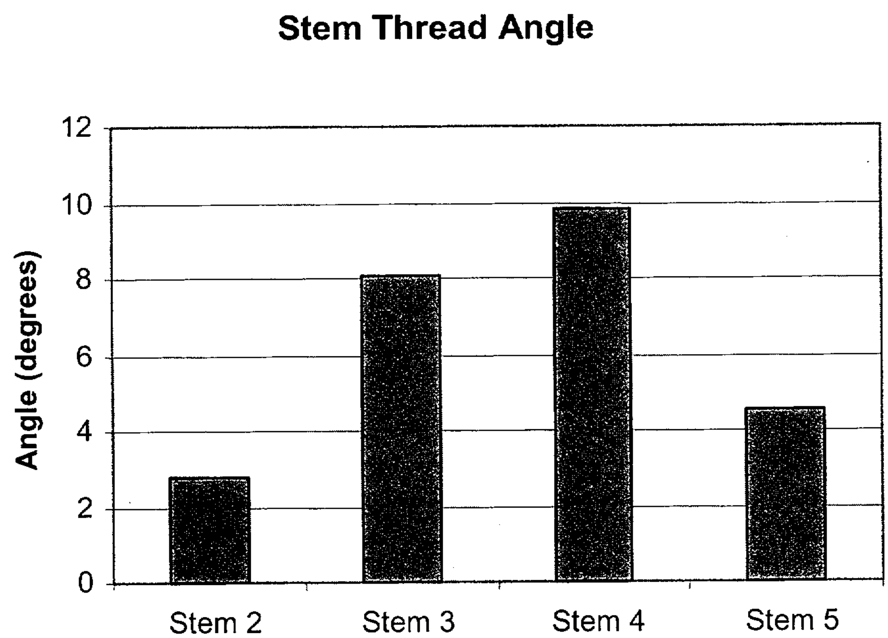

Figure 33. Stem thread angle for each stem tested at elevated temperature.

Stem 2

Stem 2 is a 1¾-inch diameter stem with a ¼ inch pitch and a ¼ inch lead (single lead). It has the most gradual stem slope of any of the stems tested, with a thread angle of 2.8 degrees. Stem 2 can be characterized as being well behaved among the five strokes at cold temperatures. It becomes less consistent among the five hot strokes. This can be clearly seen in Figure 34 where all five lubricants are shown for the single step elevated temperature tests. The figure includes tests run with the Chevron SRI, the aging test (a higher torque switch setting) and the lower torque switch setting tests. The figure shows how very repeatable each set of cold strokes performed for all five lubricants. It also slows an increase in the scatter among the five strokes at 250°F. Stem 2 with Nebula EP1 exhibits a small decrease in stem friction with elevated temperature, while the other lubricants see significant increases in stem friction at elevated temperatures.

Figure 34 also shows that for the Chevron SRI in the low torque switch series (SRI LTS in the figure) we observed a significant breakdown in stem nut friction after the second stroke at hot conditions. This provides a feeling for how close we were to breakdown in the other tests. In another test with the same grease (SRI Aging) we observe no breakdown, even at higher loads.

Figure 35 contains the data from the multiple step tests. As in the single step tests, the five cold strokes are very repeatable for each lubricant in both the initial and the final cold tests. More and more scatter appears as the stem and lubricant is heated. Nebula EP1 shows little change with temperature, while the others exhibit significant increases. We see no breakdown of the Chevron SRI friction with multiple strokes but observe that the Moly 101 breaks down somewhat at 190°F and even more at 250°F.

Compared to the other stems tested, Stem 2 exhibited the lowest ESFB (Table 5 and Appendix C), all below 30%, but was the only stem to experience increasing ESFB with increasing temperature. This occurred with the Chevron SRI, Mobilgrease 28, and Moly 101. Each lubricant is characterized by a significant change in ESFB at elevated temperature.

Stem 3

Stem 3 is a 1¼-inch diameter stem with a ¼ inch pitch and ½ inch lead (double lead). It has a much steeper slope than Stem 2 (by a factor of 3), with a thread angle of 8.1 degrees. As seen in Figure 36, Stem 3 can be characterized as being well behaved among the five strokes at all temperatures, with the exception of the N-5000 Anti-Seize. The N-5000 was found to be less consistent among the five strokes for all of the stems tested. Once again, Stem 3 with Nebula EP1 exhibits a small decrease in stem friction with elevated temperature, while the other lubricants experience increases in stem friction at elevated temperatures. Stem 3 does not show a breakdown for any lubricant at any temperature.

Figure 37 contains the data from the multiple step tests. As in the Stem 3 single step tests, the five strokes are very repeatable for each lubricant at each temperature, the exception again being N-5000 Anti-seize. Three of the lubricants, Nebula EP1, Mobilgrease 28, and N-5000 show little change with temperature, while Chevron SRI and Moly 101 increase.

Stem 3 has higher ESFB performance than Stem 2 for each of the five lubricants. In the cold tests, Stem 3 exhibited higher ESFB, almost twice that seen for Stem 2. On Stem 3, each lubricant experienced a significant decrease in ESFB at elevated temperature.

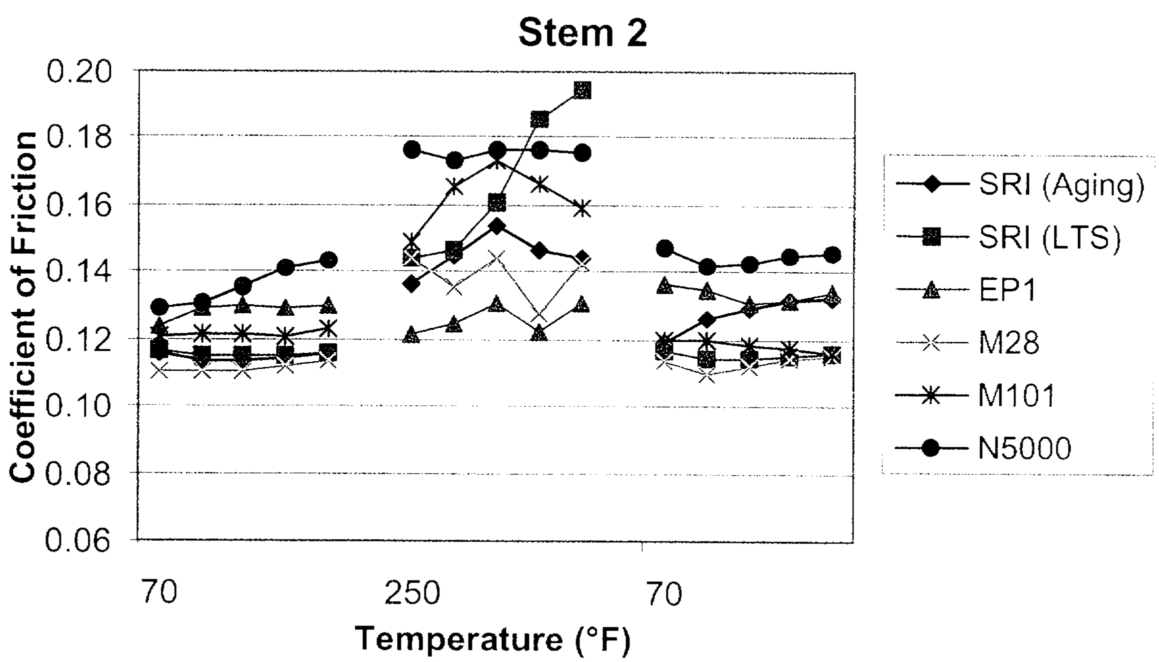

Figure 34. Stem nut coefficient of friction for each stroke of the single step tests with Stem 2.

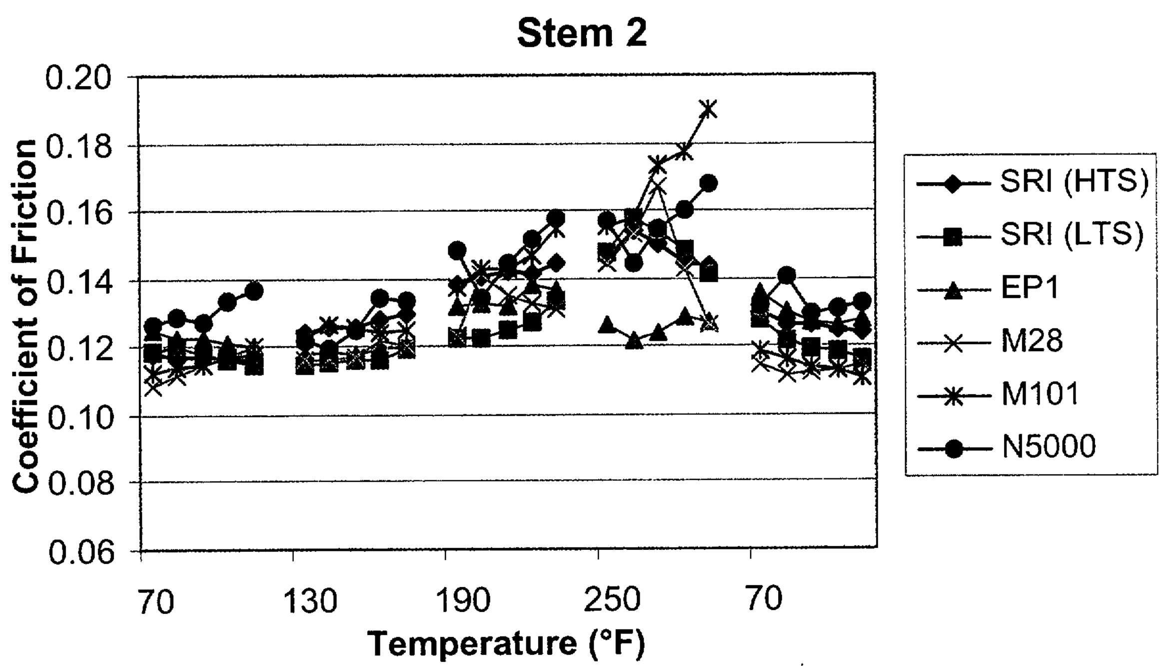

Figure 35. Stem nut coefficient of friction for each stroke of the multiple step tests with Stem 2.

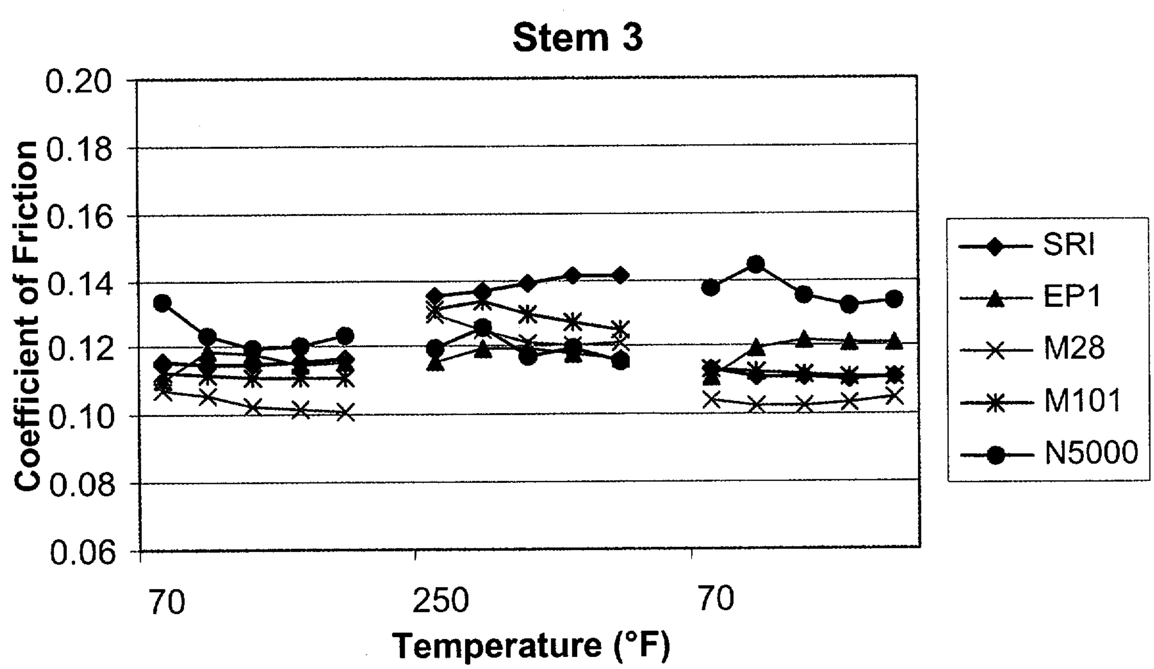

Figure 36. Stem nut coefficient of friction for each stroke of the single step tests with Stem 3.

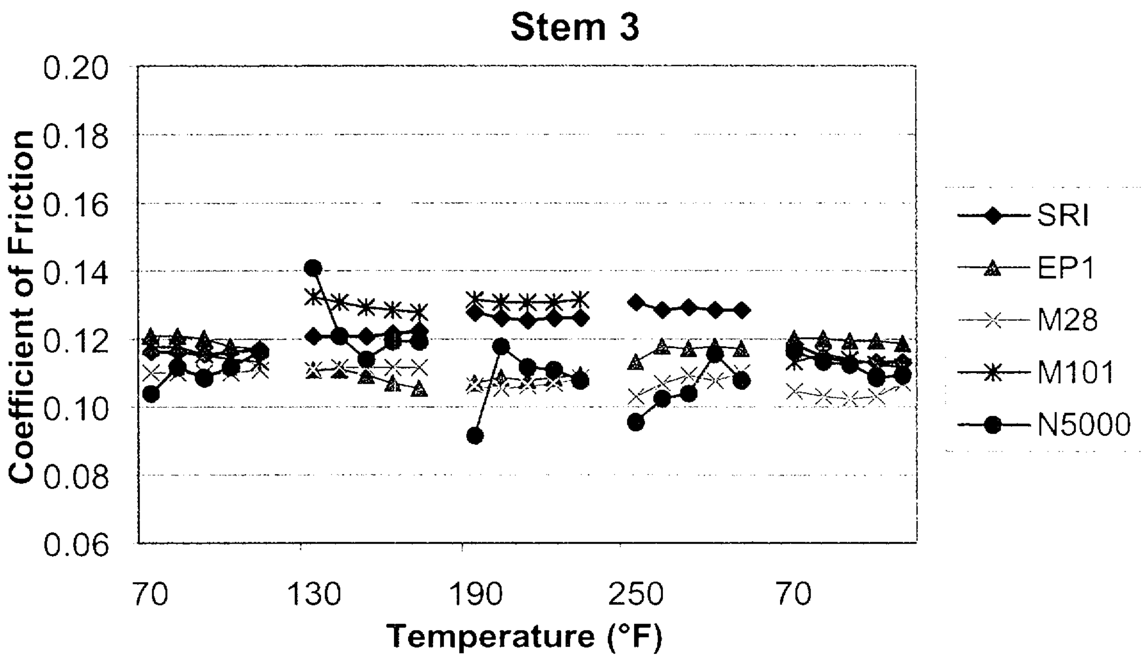

Figure 37. Stem nut coefficient of friction for each stroke of the multiple step tests with Stem 3.

Stem 4

Stem 4 is a 2-inch diameter stem with a 1/3 inch pitch and 3/3 inch lead (triple lead). It has the steepest stem slope of any of the stems tested, with a thread angle of 9.9 degrees. Stem 4 is very consistent among the five strokes for most of the temperatures and lubricants. It can be characterized as being well behaved among the five strokes at cold temperatures. It becomes less consistent among the five hot strokes. This can be clearly seen in Figure 38 where all five lubricants are shown for the single step elevated temperature tests. The figure shows how very repeatable each set of five cold strokes performed for three of the lubricants (Chevron SRI, Mobilgrease 28, and Moly 101). For these lubricants, Stem 4 shows low coefficient of friction values in the cold tests with significant increases when the stem is hot.

Stem 4 with Nebula EP1 and N-5000 has unique behavior not seen with the other stems. For the cold tests with Nebula EP1, the stem coefficient of friction starts low but climbs steadily with each stroke. It is then very stable over the five hot strokes, but continues to increase in the final cold strokes. Stem 4 with N-5000 is very high in all of the cold strokes but lower and very stable in the hot strokes, but it also slows a increase in the scatter among the five strokes at 250°F. Stem 2 with Nebula EP1 exhibits a small decrease in stem friction with elevated temperature, while the other lubricants see significant increases in stem friction at elevated temperatures.

Figure 39 contains the data from the multiple step tests. Once again we see stability among the five strokes at all temperatures for the Chevron SRI, Mobilgrease 28, and Moly 101, with significant increases in stem nut coefficient of friction with increasing temperature. The Nebula EP1 and N-5000 repeat their single step test behavior by increasing rapidly in the cold test, but remaining relatively stable at elevated temperature.

Stem 4 has highest ESFB performance of all the stems tested. In the cold tests, Stem 4 exhibited higher ESFB, almost three times higher than that seen for Stem 2. As with Stem 3, each lubricant used with Stem 4 experienced significant decreases in ESFB at elevated temperature.

Stem 5

Stem 5 is a 2 1/8-inch diameter stem with a ¼ inch pitch and ½ lead (double lead). It has a more gradual stem slope similar to Stem 2, with a thread angle of 4.6 degrees. Stem 5 can be characterized as being well behaved among the five strokes at cold temperatures and at elevated temperatures for most of the lubricants. It becomes less consistent among the five hot strokes. This can be clearly seen in Figure 40 where all five lubricants are shown for the single step elevated temperature tests. The figure shows how very repeatable each set of cold strokes performed for all five lubricants. It also slows an increase in the scatter among the five strokes at 250°F for Moly 101. Stem 5 with Nebula EP1 exhibits essentially no increase in stem friction with elevated temperature, while the other lubricants see significant increases in stem friction at elevated temperatures.

Figure 40 also shows that for the Moly 101 lubricant we observed a significant breakdown in stem nut friction after the fourth stroke at hot conditions. This provides a feeling for how close we were to breakdown in the other tests.

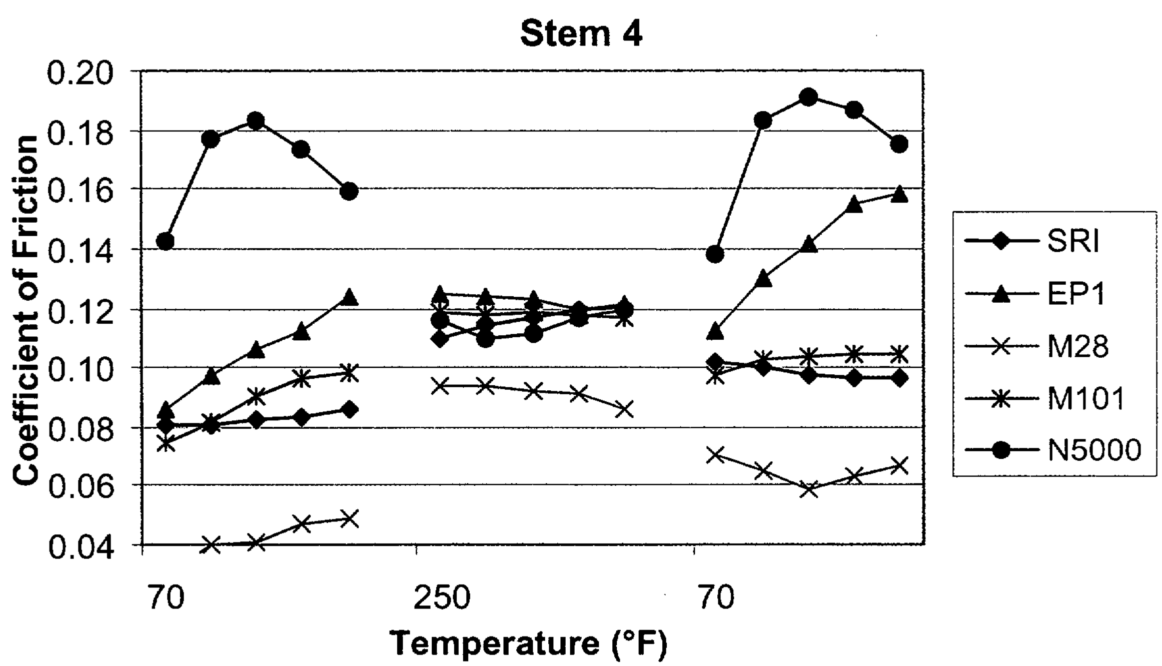

Figure 38. Stem nut coefficient of friction for each stroke of the single step tests with Stem 4.

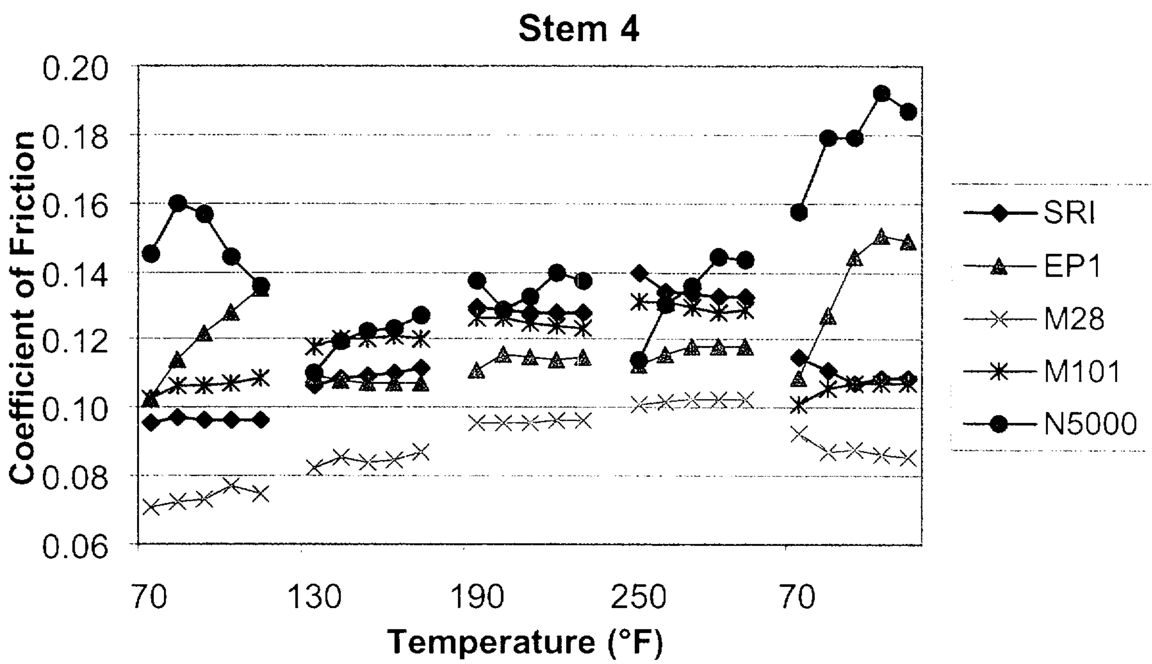

Figure 39. Stem nut coefficient of friction for each stroke of the multiple step tests with Stem 4.

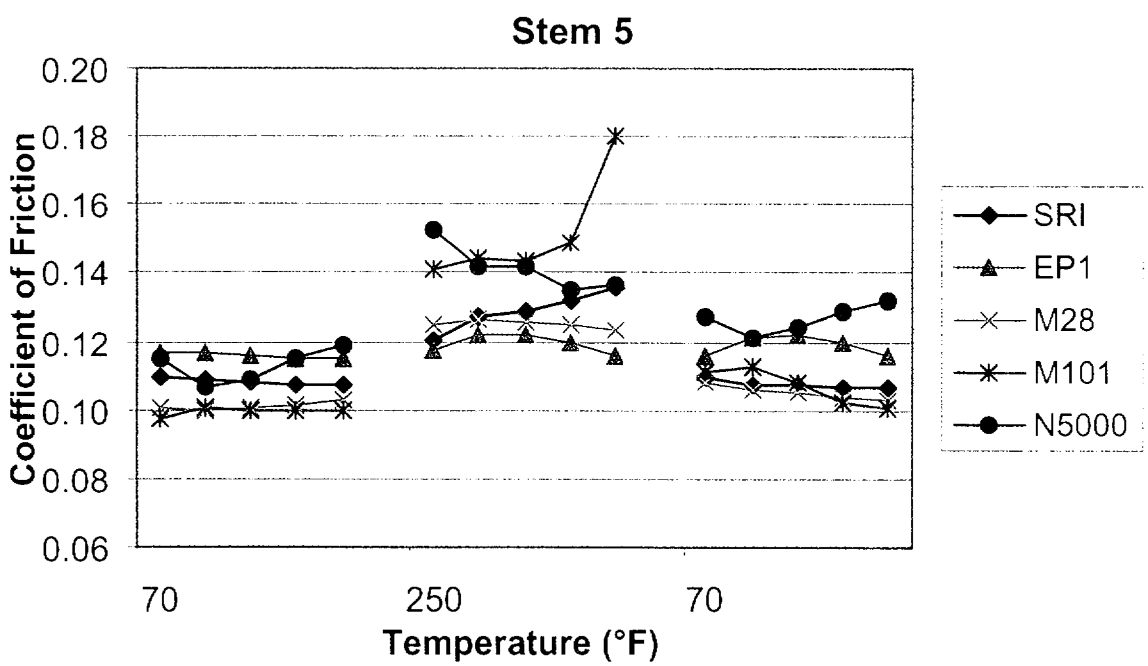

Figure 40. Stem nut coefficient of friction for each stroke of the single step tests with Stem 5.

Figure 41 contains the data from the multiple step tests. Here we see very stable performance most of the lubricants at almost all temperatures. More scatter appears at the higher temperatures. N-5000 has greater scatter than the other lubricants at all temperatures. Nebula EP1 has a slight decrease at higher temperatures, while the others exhibit increases. We see no breakdown of the Moly 101with multiple strokes, even at 250°F.

Stem 5 has lower ESFB performance than Stems 3 and 4, approximately the same magnitude as Stem 2. For Stem 5, each lubricant experienced a significant decrease in ESFB at elevated temperature.

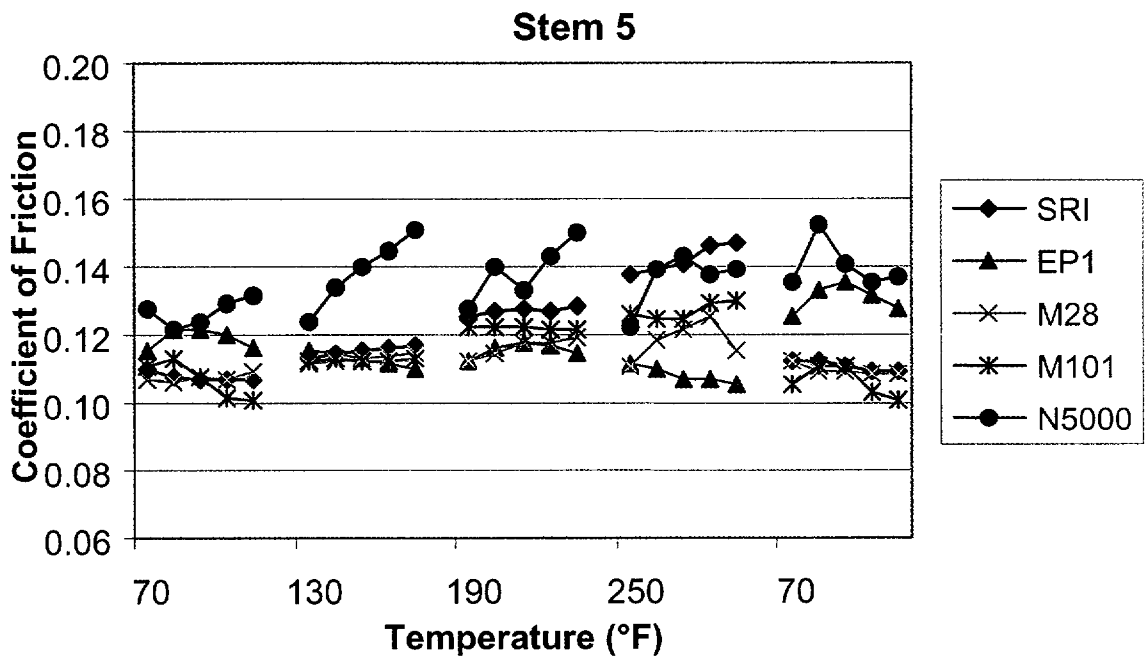

Figure 41. Stem nut coefficient of friction for each stroke of the multiple step tests with Stem 5.

5 SUMMARY

The research described in this report evaluated the effects of elevated temperature on the performance of the lubricant used on stem and stem nut configurations that are typical of those used in MOVs in U.S. nuclear power plants. Initially, the research set out to investigate how the coefficient of friction might change as the lubricant ages, using elevated temperature to accelerate the aging effect on the lubricant. However, the results from these tests showed an unexpected increase in the stem/stem-nut coefficient of friction when the temperature changed from ambient (70°F) to hot (250°F) conditions. The original lubrication accelerated aging research was postponed and the elevated temperature effect on the lubricants was investigated. The following discussion provides a summary of the results of this work:

5.1 Physical Observations

Elevated temperature conditions caused the physical characteristics of each of the lubricants to change. Some lubricants thicken at elevated temperature and some thin, allowing them to more easily move away from the loaded surfaces. In some lubricants, elevated temperatures can drive off oily components of the lubricant.

- Exxon Nebula EP1 changed from light tan to brown and had thickened. The grease returned to its original consistency by gently working the grease (rubbing a sample between our fingers).

- Chevron SRI changed from the green to dark brown and had thickened. The oils in the grease remained after heating.

- Mobil Mobilgrease 28 changed from bright red to almost black and had thickened. The oil content was reduced by heating.

- SWEPCO Moly 101 did not appear to change as a result of the elevated temperature testing.

- LOCTITE N-5000 Anti-Seize separated, with the silver component running down the stem in a separate stream from the clear component. The anti-seize moved down the stem and away from the stem/stem nut contact area.

5.2 Consistency Over Multiple Strokes

The consistency of the stem/stem nut coefficient of friction over multiple valve strokes depends upon the unique stem/stem nut and lubricant combination. For some combinations, large variations can occur between valve strokes and breakdown of stem lubrication can occur.

- Exxon Nebula EP1 produced consistent results for three of the four stems. For Stems 2, 3, and 5, the friction coefficient in the first cold stroke was often lower than in the remaining strokes. This low first stroke characteristic did not appear on the hot tests; however, Stem 2 appeared to have greater scatter among the hot strokes. Stem 4 exhibited unique behavior where the initial cold stroke had a very low friction coefficient and increased with each stroke. Hot strokes were stable with no increase, but final cold values increased dramatically.

- Chevron SRI produced results that fit into two groups. Stems 2 and 5 are very consistent in the lower temperature strokes, but can breakdown under elevated temperatures. Both stems exhibited examples of lubrication breakdown at the highest temperatures, increasing with each stroke to very high friction coefficients. Stems 3 and 4 are consistent at all temperatures tested, but at higher temperatures, they exhibit a higher first stroke with stable and slightly lower values for subsequent strokes.

- Mobil Mobilgrease 28 produced consistent results for three of the four stems. For Stems 2, 3, and 5, the five strokes performed at each temperature were very repeatable. All three stems exhibited increasing stem friction coefficients in the 250°F incremental step test. Stem 2 saw more scatter in friction coefficient at hot conditions than at cold. Stem 4 exhibited unique behavior in one of the two complete test series performed, with very low friction values, increasing with each stroke at times. This does not appear in the hot tests.

- SWEPCO Moly 101 exhibits good repeatability over the five initial cold strokes for Stems 2, 3, and 5. Stem 4 begins very low and increases with each stroke in the cold tests but becomes stable over the five hot strokes. Stems 2 and 5 show wide variations in some of the hot tests. Stem 2 and 5 experience an apparent breakdown in lubrication during the higher temperature tests.

- LOCTITE N-5000 Anti-Seize was less consistent among the five strokes for all of the stems tested, showing large variations among the five strokes for all stems, at each temperature. Stem 4 exhibits unique behavior where the initial cold baseline test and the final cold test stem friction starts high and increases dramatically from the first stroke to the second stroke. Stem 4 hot friction coefficients are lower and quite stable.

5.3 Change with Temperature

Operation at elevated temperature can have significant effects on the stem/stem nut coefficient of friction. For many of the stem/stem nut and lubricant combinations, large increases in stem nut friction occurred due to elevated temperature. Some lubricants showed no effect and some combinations produced decreasing friction.

- Exxon Nebula EP1 experienced essentially no change due to elevated temperature. The data show a slight decrease in stem nut friction at elevated temperature for all of the stems tested.

- Chevron SRI is very sensitive to elevated temperatures. All of the stems tested experienced significant increases in stem nut friction at elevated temperature.

- Mobil Mobilgrease 28 exhibits increases in stem friction at elevated temperatures for some stems but not for others. All stems show increases in friction during the single step tests. But during incremental step tests, Stem 2, the first Stem 4, and Stem 5 have increasing coefficients of friction. (Recall that Stem 4 testing was repeated due to the unusual performance in the first test series.) Stem 3 and the second Stem 4 show essentially no change with temperature.

- SWEPCO Moly 101 is very sensitive to elevated temperatures. All of the stems tested experienced significant increases in stem nut friction at elevated temperature.

- LOCTITE N-5000 Anti-Seize exhibits increases in stem friction at elevated temperatures for some stems but not for others. Stem 2 and Stem 5 show increases in friction during the single step tests, but Stem 3 and Stem 4 show decreases. During incremental step tests, Stem 3 and Stem 5 coefficients of friction do not change with temperature, while Stem 2 increases as temperature increases and Stem 4 decreases.

5.4 Change in the End of Stroke Friction Behavior (ESFB)

The end of stroke friction behavior (ESFB) dropped at elevated temperatures for most stem/stem nut and lubricant combination. Some combinations produce increasing ESFB at elevated temperature. The actual value for ESFB and the direction of change in ESFB at elevated temperature is highly dependent on the unique stem/stem nut tested and lubricant tested.

- Exxon Nebula EP1 experienced a drop in ESFB at elevated temperatures for all stems tested. Each stem exhibited a drop in the ESFB from the initial cold test to the hot test, and then a return to the higher value after cool down. The stems with more extreme ESFB under cold conditions also show the largest change in ESFB with elevated temperature.

- Chevron SRI produced changes in ESFB that were dependent on the individual stem/stem nut tested. Stem 4 had very high ESFB during cold tests and much lower during the hot tests. Stems 3 and 5 were very similar, with more typical initial values with a drop in ESFB during hot tests. Stem 2 exhibits ESFB performance where the temperature influence is reversed, beginning very low in the cold tests and increasing significantly at hot conditions.

- Mobil Mobilgrease 28 produced changes in ESFB that were dependent on the individual stem/stem nut tested. Stem 5 had the highest ESFB during cold tests and dropped significantly during the hot tests. Stems 3 and 4 were very similar, with typical initial values with a drop in ESFB during hot tests. Stem 2 exhibits ESFB performance where the temperature influence is reversed, beginning very low in the cold tests and increasing significantly at hot conditions.

- SWEPCO Moly 101 produced changes in ESFB that were dependent on the individual stem/stem nut tested. Stem 4 had very high ESFB during cold tests and much lower during the hot tests. Stems 3 and 5 were very similar, with more typical initial values with a drop in ESFB during hot tests. Stem 2 exhibits ESFB performance where the temperature influence is reversed, beginning very low in the cold tests and increasing significantly at hot conditions.

- LOCTITE N-5000 Anti-Seize exhibited ESFB performance that was much more consistent among the four stem/stem nut combinations. Stem 4 no longer has extremely high ESFB performance, dropping values very similar to Stem 3. Both exhibit moderate drops in ESFB at elevated temperature. Stem 5 shows almost no change in its ESFB with elevated temperature. Stem 2 has ESFB performance that is back to normal. dropping at elevated temperature.

5.5 Stem – Stem Nut Performance

Each individual stem and stem nut combination appear to have unique characteristics with regard to the amount of variation between strokes, elevated temperature performance, and end of stroke friction behavior.

- Stem 2 was well behaved among the five strokes at cold temperatures, but became less consistent among the five hot strokes. This was true for all five lubricants tested. At elevated temperature, Stem 2 was very near the point of lubrication break down for Chevron SRI, SWEPCO Moly 101, and LOCTITE N-5000 Anti-Seize. Stem 2 exhibited the lowest ESFB, but was the only stem to experience increasing ESFB with increasing temperature.

- Stem 3 was well behaved among the five strokes at all temperatures, with the exception of the N-5000 Anti-Seize. Stem 3 with Nebula EP1 exhibited a small decrease in stem friction with elevated temperature, while the other lubricants experience increases in stem friction at elevated temperatures. Stem 3 did not show a breakdown for any lubricant at any temperature. Stem 3 exhibited higher ESFB, almost twice that seen for Stem 2, and each lubricant experienced a significant decrease in ESFB at elevated temperature.

- Stem 4 was very consistent among the five strokes for most of the temperatures and lubricants, with two exceptions. With Nebula EP1 and N-5000 the stem coefficient of friction starts low but climbs steadily with each stroke during the hot tests. It is very stable over the hot strokes, but continues to increase in the final cold strokes. Stem 4 has highest ESFB performance of all the stems tested and experienced significant decreases in ESFB at elevated temperature.

- Stem 5 was well behaved among the five strokes at cold temperatures and at elevated temperatures for most of the lubricants. It becomes less consistent among the five hot strokes. Stem 5 with Nebula EP1 exhibits essentially no increase in stem friction with elevated temperature, while the other lubricants see significant increases in stem friction at elevated temperatures. Stem 5 with Moly 101 saw significant breakdown in stem nut friction after the fourth stroke at hot conditions. Stem 5 has lower ESFB performance than Stems 3 and 4, and approximately the same magnitude as Stem 2, and each lubricant experienced a significant decrease in ESFB at elevated temperature.

5.6 Influence of Aging on Exxon Nebula EP1

At room temperature the stem nut performance was consistent with earlier testing. The observed anomalous stem nut performance was caused by degradation in the lubricant properties at hot conditions. Our Nebula EP1 lubricant had exceeded the recommended shelf life and was used near the recommended operating temperature limit. This recommended shelf life limit is not common knowledge in the nuclear industry. Our data supports the use of the Nebula EP1 lubricant inside the gearbox both at elevated temperature and beyond the two-year shelf life.

- Testing of the aged (~10 years stored at room temperature) Exxon Nebula EP1 indicated a notable loss in lubricant performance at the 250°F test temperature. This experience tends to reinforce the manufacturer's recommended two-year shelf life for this product.

- The typical use of Nebula EP1 in actuator gearboxes exceeds the Exxon recommended shelf life. However, the Limitorque environmental qualification at 340°F supports use at the temperatures encountered in our testing. Exxon does not provide a recommended service life for EP1; however, operating experience and existing test data support use as a gearbox lubricant beyond the recommended shelf life.

- The results of the initial accelerated aging tests showed an unexpected increase in the stem/stem-nut coefficient of friction when the temperature changed from ambient (70°F) to hot (250°F) conditions. This clearly indicated the need to revise the testing scope to properly investigate the effects of elevated temperature on lubricant performance and to observe the differences in performance of different lubricants with several stem/stem nut configurations.

- Initial cold tests with Stem 2 and the aged EP1 yielded stem nut performance consistent with earlier testing. The observed anomalous stem nut performance at elevated temperature was caused by degradation of the lubricant properties at hot conditions. As noted above, the aged EP1 lubricant had exceeded the manufacturer's recommended shelf life and was used near the

250°F recommended operating temperature limit. This recommended shelf life limit is not common knowledge in the nuclear industry.

CONCLUSIONS

This research effort was performed to address the effectiveness of the lubricant used on the threaded portion of the valve stem. The effectiveness of this lubricant can greatly impact the thrust output of the valve actuator and reduce the margin for ensuring MOV performance at design basis. Our analysis looked at the performance of five lubricants on four stem and stem nut combinations. The following conclusions are based on this work.

- The physical characteristics of each lubricant change at elevated temperature. Some lubricants thicken while others thin, allowing the lubricant to move away from loaded surfaces. Some lubricants lose their oily components.

- The repeatability of the stem friction coefficient over multiple strokes depends upon the unique stem/stem nut and lubricant combination. Large variations in stem friction can occur between strokes. Complete breakdown of the stem lubrication can occur.

- Operation at elevated temperature can have a significant effect on the stem coefficient of friction. For many of the stem, stem nut, and lubricants, large increases in stem nut friction occurred. Some lubricants showed no effect and some stem/stem nut combinations produced decreasing friction.

- The value and the direction of change in the end of stroke friction behavior (ESFB) is highly dependent on the stem/stem nut and lubricant being tested.

- Each individual stem and stem/nut combination has unique characteristics with regard to the repeatability of the stem friction coefficient over multiple strokes, the elevated temperature performance, and the ESFB.

- Lubricant aging can cause the stem/stem nut coefficient of friction to increase.

7 REFERENCES

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