SELECTION OF GREASES FOR MOTOR-OPERATED VALVE STEM/STEM NUT LUBRICATION

Fabrice M. Guérout, Jean-Marie Pitard-Bouet°, Christophe Jouve°, and John Janis*

Atomic Energy of Canada Limited
Chalk River Laboratories
Chalk River, Ontario
Canada K0J 1J0
E-Mail: gueroutf@aecl.ca

°Electricité de France, R&D Division
* Ontario Power Generation

ABSTRACT

In Motor-Operated Valves (MOV), the choice of a high-performance grease for stem/stem nut lubrication is required to guarantee long-term operability. Valve stem regreasing intervals and/or actuator limit switch resetting intervals of less than two years are no longer acceptable to most stations, because of the large number of valves in service.

A joint MOV test program was launched in 1995 by Atomic Energy of Canada Limited (AECL), Electricité de France (EDF) and Ontario Power Generation (OPG) to select the best grease candidates available and address issues relative to valve reliability, increased maintenance costs, and environmental protection. The objective of this research was to identify greases that would be suitable for 4 to 5 years in service without regreasing.

A thermal aging procedure was developed by OPG to simulate a five-year exposure to the in-service temperatures experienced by valve stem/stem nut arrangements. The grease candidates were initially screened using data from pin-on-disk wear tests and/or results of thermal aging tests. The thermal aging tests screened for grease consistency variations, acidity build-up, etc. Samples thermally aged for the equivalent of five years in service were then used for mechanical tests in a full-scale MOV test rig developed by AECL and EDF at the Chalk River Laboratories (CRL). The assessment of the stem/stem nut lubrication condition was mainly based on stem/stem nut friction coefficient measurements (value and stability of this value with valve stroke number).

In this paper, the effect of grease thermal and mechanical aging on stem/stem nut lubrication is assessed, along with the effect of high temperature and high irradiation levels (accident conditions). The MOV test results are compared according to the type of base oil and thickener used in the grease. The effect of stem material and stem geometry on stem/stem nut lubrication is investigated. Results obtained for grease mixtures are also reported. Finally, grease specifications recommended to maintain adequate long-term MOV stem/stem nut lubrication are provided.

INTRODUCTION

Greases are used at the valve stem/stem nut location to protect both threaded parts in contact and to ensure that torque developed within the motor-operator is efficiently converted into stem thrust to operate the valve. This efficiency can be greatly affected by the type of grease used and by the effect of thermal aging, mechanical aging and other environmental parameters, such as temperature or radiation, on grease condition.

One of the many challenges facing nuclear power plant operators is the improvement of MOV lubrication conditions to maintain long-term component operability and reduce costs associated with MOV maintenance programs. Valve stem regreasing intervals or torque limit switch resetting intervals of less than one or two years are no longer acceptable to most stations, considering the large number of MOV's in service. The use of very stable, low-friction greases for stem/stem nut lubrication is the key to long-term valve operability and limited maintenance costs.

At the request of several nuclear power generating stations in Canada, an MOV grease test program was started at AECL, Chalk River, and at OPG, Toronto, in 1995. A collaboration with EDF was launched in 1996 and a full-scale MOV test rig dedicated to MOV grease selection was developed. A specific procedure including the testing of grease thermal and mechanical aging properties and post-test evaluation of grease characteristics was put in place. More than thirty grease candidates were tested and ranked in accordance with criteria and key parameters as defined through consultations with station valve and lubricant specialists.

This paper summarizes the results obtained for the various types of grease tested. The test results are compared according to grease composition (type of base oil, type of thickener, and additives used). The effect of thermal and mechanical aging on grease performance is studied along with the effect of high temperature and high irradiation levels. Based on this study, the grease characteristics required for adequate long-term stem/stem nut lubrication of motor-operated valves are specified.

BACKGROUND

Stem/stem nut lubrication characteristics

In MOV's, valve stroking is generated by an electrical actuator that provides a torque for stem nut rotation. The rotation of the stem nut induces the vertical translation of a threaded stem/valve gate arrangement that results in flow isolation. The efficiency of the torque/thrust conversion is a function of stem/stem nut geometry and of friction properties at the stem/stem nut location (Equation 1).

$$F = \frac{Torque}{Thrust} = R\frac{\tan(\alpha) + \dfrac{\mu}{\cos(\beta)}}{1 - \tan(\alpha)\dfrac{\mu}{\cos(\beta)}} \qquad (1)$$

where F = Stem Factor (in meters), R = Average Thread Radius (in meters)= 0.5 x (Thread Diameter (in meters) - 0.5 x pitch), $\beta = 14.5°$ (ACME thread), $\tan(\alpha) = \text{lead}/(2\pi R)$, and lead = pitch x number of start threads (in meters).

For given loading conditions, the stem/stem nut friction coefficient depends, to some extent, upon the characteristics of bearing surfaces but is in fact mostly related to the properties of the lubricant used at the stem/stem nut location. Therefore, changes in lubricant condition as a result of mechanical aging or as a result of the effect of environmental parameters may have a significant effect on the thrust delivered for a given torque and have serious implications. On one hand, increasing stem/stem nut friction coefficients can result in stem thrusts generated at torque switch trip that are not sufficient to properly close the valve. A significant decrease of friction coefficient can, on the other hand, cause overloading of the valve. Also, design guidelines for proper actuator operation sometimes require that the friction coefficient remains below a pre-set value (i.e., 0.15 for EDF power plants).

Greases are preferred lubricants for open systems such as the stem/nut arrangement in MOV's, where the lubricant must maintain its original position in the mechanism. A grease consists of a base oil (80 to 95% of grease weight), a thickener, and additives. Grease lubricity is usually determined by base oil properties, especially base oil viscosity. Grease consistency and rheological properties are determined by the type of thickener used. Anti-oxidation, anti-wear, extreme pressure, anti-corrosion additives, solid lubricants, or soft metal particles are added to enhance grease performance.

Requirements from station end-users

If a grease used for stem/stem nut lubrication is not the best from an operability or from an environmental qualification point-of-view, the benefit of using a new grease must be clearly demonstrated prior to stem/stem nut grease replacement. The grease characteristics must satisfy the requirements associated with valve mechanical performance, valve environment, and economic benefit.

There are many requirements relative to valve mechanical performance. The stem/stem nut arrangement in MOV's is typical of a "high load/low speed" lubricated mechanism. Therefore, in order to maintain a film of lubricant between the loaded bearing surfaces, the use of Extreme Pressure (EP) greases (or products with similar characteristics) is required. As mentioned above, based on design guidelines, the friction coefficient must sometimes be kept below pre-set values (for EDF power plants). The emphasis is also put on friction coefficient stability to avoid frequent resetting of torque switch trip values, the possibility of improper closures (increasing friction coefficient), or valve overloading (decreasing friction coefficient). The overall mechanical performance of the stem/stem nut arrangement must remain quasi-unchanged throughout the regreasing interval chosen, whether the valve is actuated several times a day or only once a year. A small difference in thrusts developed at torque switch trip under static and dynamic loading is also preferred (i.e., low grease sensitivity to Rate-of-Loading (ROL) effects).

The impact of the nuclear reactor environment on grease performance must also be considered when selecting potential grease candidates. The grease must have antioxidation properties because of the relatively high in-service temperatures (45 to 60°C in many parts of the reactor building). The concentration of additives found in many EP or anti-wear greases (such as chlorides or sulfur) is often above the limits set by the industry regulators (usually 400 or as low as 200 ppm allowed). This drastically restricts the number of EP greases to be considered. The greases must also withstand in-service radiation levels (up to 10 Mrad over 5 years) and resist conditions resulting from Loss Of Coolant Accident (LOCA) or Major Steam Line Break (MSLB). Naturally, high-temperature greases would be preferred candidates to guarantee valve operability at peak temperatures of 165°C and accident steady temperatures of 110-120°C. The resistance of the grease to high irradiation levels must also be demonstrated (if adding in-service, LOCA, and post-LOCA irradiation). Resistance to water or steam washout and to chemical attack would also be an asset in the event of an accident.

A major issue is also the extensive cost associated with the maintenance and monitoring of the large population of MOV's in service at each plant. Valve stem regreasing intervals or torque limit switch resetting intervals of less than one or two years are no longer acceptable. Access to many valves is restricted and short regreasing intervals often mean increased radiological doses to workers and increased amounts of waste for disposal. Therefore, a reasonably priced, high-performance grease, suitable for 4 to 5 year regreasing intervals, is required.

OBJECTIVES

The stem/stem nut lubrication is a specific industrial application and there are many requirements to be satisfied in order to guarantee that the lubricant can safely be used in MOV's. For commercial reasons, information such as the nature of the additives, the fabrication process, or the thickener/oil ratio are rarely disclosed to the end users. Therefore, the selection of a grease candidate solely based on grease properties available from grease manufacturers is not recommended.

Several standard tests can be used to study grease characteristics (oxidation resistance, wear resistance, etc.) but they are not representative of MOV stem/stem nut lubrication conditions and would not provide the information relative to friction coefficient that is absolutely needed in this case.

Therefore, the main objective was to develop a test rig that closely reproduced the MOV operating conditions (both in-service and accident conditions). This would allow the best grease candidates to be selected according to the requirements outlined in the previous section.

However, accelerated mechanical testing in an MOV test rig cannot take into account the effect of long-term exposure to in-service reactor conditions. Therefore, another objective was to develop a test procedure for representative thermal aging and irradiation of the grease candidates prior to MOV testing.

DESCRIPTION OF TEST FACILITY AND GREASE TESTING METHODOLOGY

Thirty-six grease candidates were initially considered by OPG (24) and EDF (12) for use at the stem/stem nut location. The initial list consisted of products already used at the various sites, products recommended by grease manufacturers, or products selected based on some of their basic properties (i.e., EP properties or high-temperature resistance).

Pin-on disk tests

Pin-on-disk testing was used by OPG to select 12 greases from the initial list. The pin-on-disk test is a standard test (ASTM G-99) that consisted of rotating a disk at constant speed against a pre-loaded, stationary pin for 60 minutes. The grease to be tested is applied onto the disk prior to the test. The Herguth Wear Rating (HWR) formula (Equation 2) is used to rank the grease candidates. The lower the rating, the better the grease from a lubrication and wear point-of-view.

$$HWR = (100f) + (1000V) + (4.7DR) \qquad (2)$$

where f = friction coefficient, V = pin wear volume, and DR = visual disk rating from 1 to 10

This type of test is valuable for preliminary screening of a large number of grease candidates, but it may not be the most adequate selection tool. Some of the EDF greases with high HWR's appeared to be very successful candidates during the MOV test campaign while greases with very low HWR's did not necessarily do well in the MOV test rig. There are significant differences between a pin/disk contact and a stem/stem nut contact. Also, the HWR does not account for the stability of measured parameters with time. Therefore, pin-on-disk tests should not be used for MOV stem/stem nut grease qualification.

Thermal aging and irradiation of selected grease candidates

The objective was to thermally age and irradiate all grease candidates prior to MOV testing to simulate long-term exposure to in-service temperature and radiation (5 and even up to 8 years at 45-60°C and 100 kGy over 5 years).

Accelerated thermal aging can be obtained at elevated temperature in a relatively short period. The limiting factor is the sensitivity of additives to high temperature. An Arrhenius model of thermal aging (Equation 3) is generally applicable to greases [1]:

$$t = t_0 \exp(\frac{Q}{RT}) \qquad (3)$$

where t = Exposure Duration, t_0 = Constant, Q = Activation Energy, R = 8.314 $kJ.K^{-1}.mol^{-1}$ (constant), and T = Temperature in K.

Nowadays, EP additives used in premium extreme pressure lubricants can easily survive test temperatures of up to 135°C without premature decomposition. Thermal aging of the various grease candidates was performed in an oven either at 120°C for 8 weeks or at 130°C for 4 weeks. Similar aging temperatures and durations have been used by others [2, 3]. The 130°C aging condition was used for rapid product screening while the 120°C condition was used for aging "short listed" products prior to MOV mechanical testing. According to Equation 3, this is equivalent to five-years of aging at 77°C.

For thermal aging in the oven, the characteristics of the stem/stem nut arrangement (vertical open system using a thin layer of grease) must be taken into account. Therefore, all grease samples were applied to vertical steel panels. The grease on each panel was 2 mm thick, and was redistributed on the test panel at the equivalent of 7.5 months of ambient aging. This redistribution served two purposes: (1) it simulated occasional valve stroking, and (2) it ensured that all portions of the grease sample were regularly exposed to air. Good air exposure is required so that oxygen does not become a limiting reactant in grease oxidation reactions introducing non-Arrhenius effects.

The end-of-life criteria were chosen to be most relevant to the type of transformation that would affect grease performance at the stem/stem nut location. The end-of-life criteria adopted for grease aging resistance were: (1) a two grade change in grease consistency (a two grade loss would be a sign that the grease could run out of the stem/stem nut arrangement, while a two grade gain could result in nut jamming); (2) an 80% loss in acid buffering capacity or an absolute Total Acid Number (TAN) limit of 3 (which would indicate excessive grease oxidation); and (3) extreme slumping from vertical panels or other gross property changes during the aging process. Grease weight loss was also monitored but was not used as an end-of-life criterion.

At the end of the five-year aging period, all vertical panels were gamma (Cobalt 60) irradiated at room temperature to a dose of 100kGy (10 Mrad) at a dose rate of approximately 1-3 kGy/h (0.1-0.3 Mrad/h). This exceeds a usual five year in-service dose and is intended to simulate a worst case service condition.

Mechanical testing in MOV test rig

The objective was to compare the grease performances using a test stand that is representative of Motor-Operated Valves used at the stations. To this end, a valve body and a valve actuator were purchased and assembled. The MOV grease test rig was then built around these two major components, and includes the following items:

- mechanical assembly for supporting the valve body
- Velan ANSI 150 valve body (8" diameter)
- Limitorque SMB.0 actuator
- valve packing for static loading
- bronze nut
- stainless steel stem
- mechanical assembly for dynamic loading
- MOVATS cell for on-line measurement of torque, thrust, and friction coefficient
- sensor for on-line measurement of stem displacement
- unit for motor current measurement
- counter and relays for control-command
- PC and SNAP MASTER software for control-command and signal acquisition.

A schematic of the CRL grease test stand is shown in Figure 1.

A mechanical assembly was developed to generate side forces and simulate differential pressure effects from the process fluid on the valve gate during valve operation. These side forces result in stem dynamic loading through friction forces generated at the gate/valve body interface.

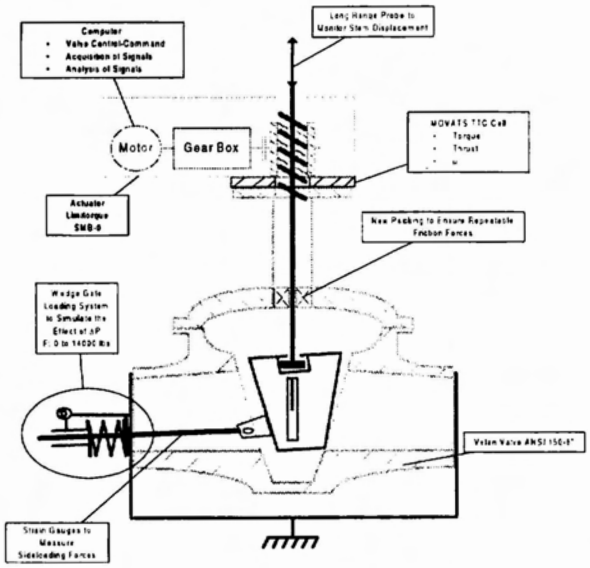

Figure 1: MOV Test Rig

The core of the dynamic loading assembly consists of a main shaft and a set of Belleville washers of two different sizes. The shaft is connected to the lower half of the valve gate. It rotates around two axes and slides in a fixed bearing housing in order to accommodate the gate displacement. The shaft displacement results in Belleville spring compression and sideloading of the valve gate. The spring set is assembled to generate 53 kN in the horizontal direction in the closed position (equivalent ΔP of 1.13 MPa). This results in 20 kN of additional "dynamic" thrust on the stem. The washer arrangement is designed to generate low dynamic loading of the stem during most of the valve closing sequence and highly increased loads at the end of the closing sequence.

The mechanical assembly developed at CRL provides a good reproduction of a typical MOV dynamic load-time history for both opening and closing sequences.

The differential pressure simulation system offers a cost effective alternative to valve test rigs using flow generated by a circulation loop Compared to "static" systems, it also has many advantages in view of MOV grease selection:

- the greases will be stressed using representative stem thrusts and side forces,
- the system allows the comparison of thrusts near Torque Switch Trip (TST) for dynamic strokes (lower loading rates, i.e., increasing stem thrust throughout closure cycle) and static strokes (higher loading rates, i.e., increasing stem thrust only at end of closure cycle). This will be useful to assess the grease sensitivity to rate-of-loading (ROL) effects,
- unlike vertical springs sometimes used to reproduce dynamic loading, the CRL mechanical assembly generates a sudden thrust variation at valve unseating which is representative of the stem compression/ traction transition phase. This sudden thrust variation at the beginning of the opening stroke allows a representative brisk redistribution of the grease on the opposite side of the thread. This effect would not be simulated using a vertical spring system (i.e., the stem would remain loaded on the same side of the thread).

The preparation, performance, and analysis of each grease selection test consisted of the following steps:

1) A new bronze nut was used for each test. The bronze nuts were manufactured at CRL to ensure that consistent thread geometry was used. Both nut and stem were thoroughly cleaned (using chloride and sulfur free products) and were greased (25 ml of grease evenly spread on both parts) using the product to be tested
2) Stem and nut were installed in the valve, along with a new packing.
3) Valve yoke and actuator were assembled and 10 static closing and opening sequences for packing positioning and set up of packing load were performed.
4) The mechanical assembly to simulate differential pressure effects was attached to the valve.
5) A series of 240 dynamic opening and closing sequences were performed to assess the effect of valve stroking (i.e., mechanical aging) on stem/stem nut lubrication. A rest period of 3 min was allowed between each stroke.
6) After removal of the sideloading system, five static closing and opening sequences were performed.
7) The valve body, actuator, stem and nut were disassembled and grease samples were taken for post-test analysis.
8) The data were analyzed and the grease performance was assessed

For each grease, several tests of this type were performed using a new formulation and thermally aged formulations (5 year and 8 year equivalent).

Grease rating criteria were selected in consultation with station valve and lubricant specialists. For the rating process, weighting factors were assigned based on the impact of each parameter on valve operability. From a mechanical point-of-view, a high-performance grease will show:

- low friction coefficients (especially for high thrusts reached while ΔP is simulated or during valve seating)
- stable friction coefficient with increasing stem load and stroke number
- stable thrust at TST with increasing stroke number
- low sensitivity to thermal aging effects.

Curves in Figure 2 show that the MOV test rig results will discriminate between low-performance and high-performance greases. For example, the friction coefficient for Grease A is very unstable with increasing stroke number, while both tests with Grease B show stable results. Grease C exhibits the best characteristics with a low and relatively stable friction coefficient. Test results for a given grease candidate were repeatable within ± 5% (see Test #1 and Test #2 for Grease B). The accuracy of friction coefficients measured while ΔP is simulated and during valve seating was 1.2 and 0.9% respectively. The accuracy of thrust measured at 185Nm was 0.8%.

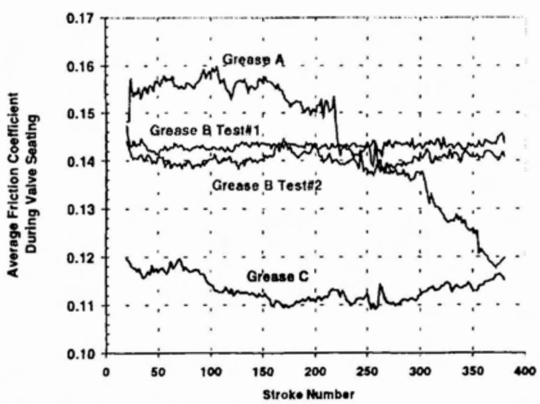

Figure 2: Comparison of Friction Coefficients Measured During Valve Seating for Three Different Greases.

The effect of the rest period duration between strokes was studied. Similar friction coefficients were measured after rest periods of 3, 20, 40, 80, or 1000 minutes as shown in Figure 3. However, rest periods of 1 minute or less were shown to affect friction coefficient stability. Therefore, a 3 minute rest period was chosen as the best compromise in order to generate relevant test results within reasonable time periods.

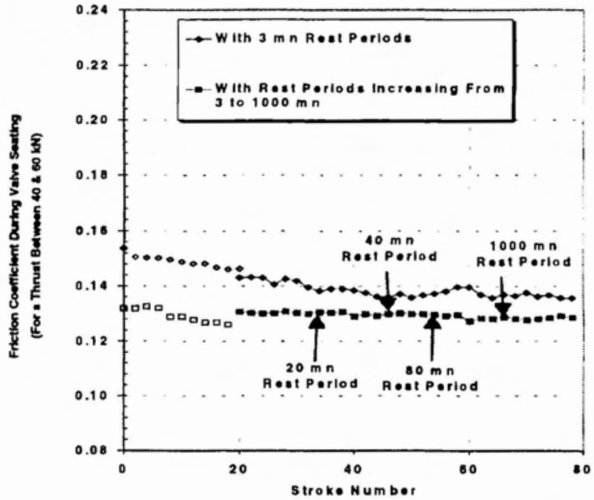

Figure 3: Effect of Rest Period Duration on Friction Coefficient Stability.

Post-test analysis of grease samples

Grease samples were collected from three parts of the stem (top, middle, and bottom). The amount of grease collected was only in the order of 1 to 5 g, but sufficient for post-test analysis. Post-test analysis consisted of microscopic evaluation of wear debris, a deleterious particles test, trace element analysis, and penetration measurements using the Dynamic Mechanical Analyzer (DMA), which was developed to determine penetration on samples of less than 1 g.

THERMAL AGING RESULTS

Greases aged at 40°C during 1.4 years and aged the equivalent of 1.25 years at 120°C showed similar consistency after the test. Therefore, a thermal aging duration-temperature equivalence based on the Arrhenius model proved to be suitable for accelerating the thermal aging process.

Only nine out of twenty-four greases initially selected by OPG and EDF met all criteria for resistance to thermal aging during 5 years at 45 to 60°C. Some greases slumped from the vertical panels and many showed unacceptable changes in consistency and/or buffering capacity. However, some of the best greases withstood the equivalent of 8 years at in-service temperatures.

Most high-temperature greases (i.e., maximum service temperature recommended by grease manufacturers is above 150°C) showed good resistance to thermal aging, but not all.

MOV TEST RIG RESULTS

Effect of the type of grease (base oil, thickener, additives combination) on MOV lubrication characteristics

Friction coefficients measured during the application of side forces (simulation of ΔP) and during valve seating and thrusts measured near TST are shown in Figure 4 for 5 different families of greases according to their composition (various base oil-thickener-additives combination). The range of friction coefficients obtained was relatively wide, from 0.10-0.11 up to 0.17. For most greases tested, the average friction coefficient was approximately 0.14.

One must be cautious when comparing results according to the grease type because the amount of information released by grease manufacturers is usually minimal and does not include the nature of additives or the proportions of base oil and thickener in the grease. However, some interesting trends were observed. The lowest friction coefficients were found for greases using a synthetic PAO base oil and a clay thickener (#1 and #2 in Figure 4). With mineral oils, the friction coefficients were usually around or above 0.14, except for the value of 0.13 obtained for the mineral-clay combination (#5 in Figure 4). Therefore, using clay as a thickener seems to decrease friction at the stem/stem nut location. The comparison of grease types 6a and 6b (Figure 4) shows that the presence of EP additives can also decrease friction. However, EP additives are not always required to obtain low friction coefficients at the stem/stem nut location (grease types #1, 2, and 5 do not contain EP additives yet exhibit the lowest friction coefficients).

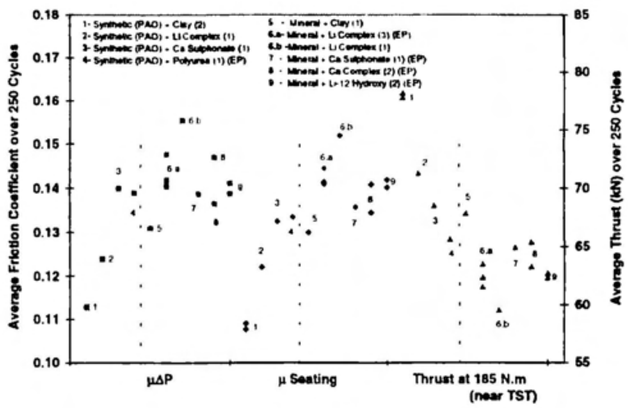

Figure 4: Comparison of Average Friction Coefficients and TST Thrusts for Various Types of Unaged Greases.

For EDF applications, the actuator tripping point set up is based on equations that use a friction coefficient of 0.15. In that case, lower friction coefficients such as 0.10 obtained for the synthetic PAO - clay combination are preferred since the margin from the 0.15 design value becomes larger. For OPG applications, the actuator tripping point set up is based on the thrust value obtained for a given torque. Therefore, the stem thrust developed at Torque Switch Trip and the stability of this thrust value with stroke number and time are key parameters.

Effect of mechanical aging on MOV lubrication characteristics

The variation of TST thrust and friction coefficient over 250 MOV opening and closure cycles is shown in Figure 5. For most greases, this variation does not exceed 5-10%. The type of grease recommended for good stability with increasing stroke number uses the mineral base oil - lithium complex thickener combination (#6a in Figure 5). One of the greases that contained a calcium complex thickener (#8 in Figure 5) proved very sensitive to mechanical aging (variations of parameters of up to 30-35% after 250 cycles).

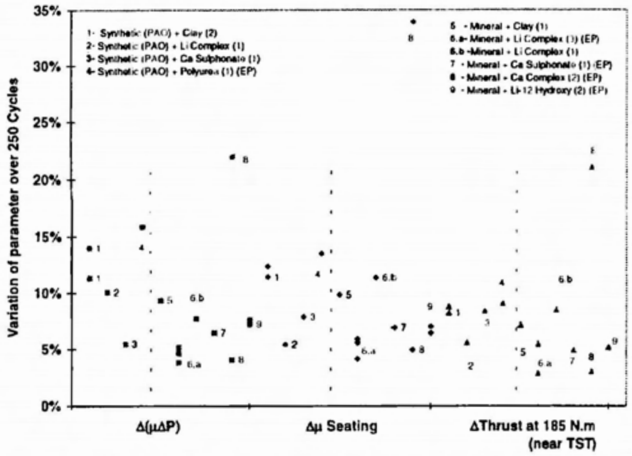

Figure 5: Comparison of Parameter Stability over 250 Cycles for Various Types of Unaged Greases.

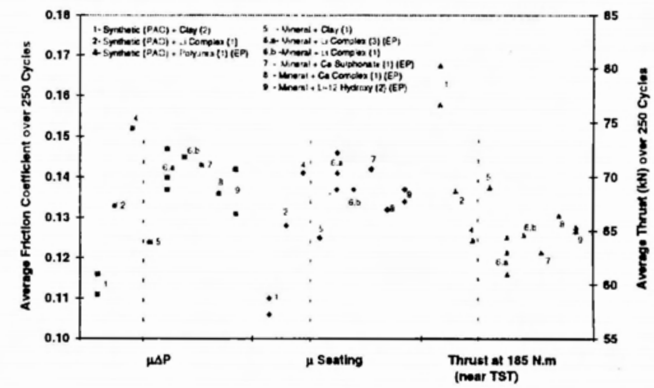

Figure 6: Comparison of Average Friction Coefficients and TST Thrusts for Various Types of Thermally Aged Greases (5 Year Equivalent).

Effect of thermal aging on MOV lubrication characteristics

Five-year equivalent thermally aged greases were tested in the MOV rig to assess the effect of thermal aging on stem/stem nut lubrication. Thermal aging resulted in either slight softening or hardening of the greases, depending on their composition. However, these changes in consistency could not be related to friction coefficient variations. Results for friction coefficients are shown in Figure 6. For most 5-year aged formulations, the friction coefficients are very similar to those obtained when using the unaged formulation. The difference between the two sets of results usually does not exceed 10%. This is not entirely surprising because most greases selected for MOV testing were amongst the best candidates from the thermal aging screening process described earlier in this paper.

Most 5-year aged formulations showed fair resistance to mechanical aging. The variation of friction coefficients and thrusts with increasing stroke number ranged from 10 to 20% over 250 cycles for most greases tested (Figure 7). The friction coefficients obtained for the 5-year aged formulations were usually less stable than those obtained for the unaged formulations. Several greases that used lithium complex as a thickener showed higher friction coefficient and thrust stability. The grease that contained a calcium complex or a polyurea thickener showed the most friction coefficient and thrust variations. The PAO + clay greases showed friction coefficient variations over 250 cycles in the order of 20% but the average friction coefficient for the 5 year-aged formulation was still low at 0.11-0.12.

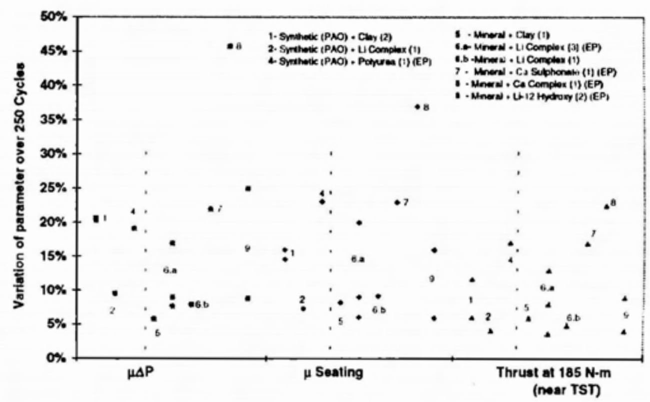

Figure 7: Comparison of Parameter Stability over 250 Cycles for Various Types of Thermally Aged Greases (5 Year Equivalent).

The best candidates were aged for the equivalent of 8 years in service. The variation of friction coefficients and thrust between 5-year aged and 8-year aged formulations is shown in Figure 8 (comparison over 50 cycles). The best candidate showed only 2% variation (mineral oil - lithium complex - EP additives combination). However, some 8-year aged formulations showed significantly decreased performance from the 5-year aged case (average friction coefficients that are 25 to 30% higher, i.e., decreased resistance to mechanical aging).

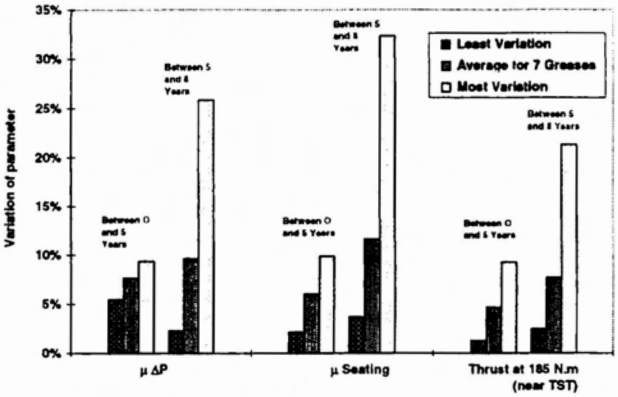

Figure 8: Variation of Average Friction Coefficient and TST Thrust between Unaged, 5-Year Aged, and 8-Year Aged formulations (Most, Least and Average Variation over 50 Cycles).

Results for grease mixtures

Mixtures should be tested because greases are sometimes replaced by a new product without full cleaning of the stem prior to regreasing. MOV tests were performed using mixtures of some of the best greases previously tested. For these mixtures, the friction coefficient was usually between the two average friction coefficients initially derived for each pure product. This trend is shown in Figure 9. However, testing was performed for a very limited number of mixtures and, more importantly, the thermal aging behavior of these mixtures was not studied. Therefore, it is advisable to fully clean the stem when replacing one grease by another.

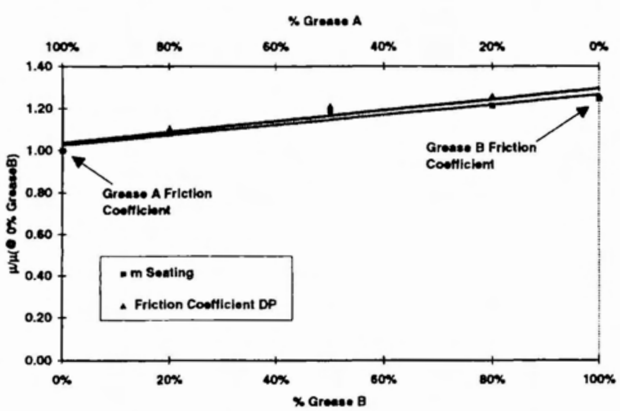

Figure 9: Comparison of Friction Coefficients Measured for Two Compatible Greases and for Various Mixtures of these Two Greases.

Effect of stem material and geometry

Stem material was 410 stainless steel for testing of the OPG greases and 17-4-PH for testing of the EDF greases. When testing similar greases with the two types of stem, it was shown that stem material had no significant effect on the stem/stem nut lubrication condition. On average, using these two different stems, the difference between friction coefficients obtained for the same grease was only about 5%. That is within the repeatability of test results for a given configuration.

For one of the greases, additional tests were performed to study the effect of stem/stem geometry on lubrication characteristics.

For a given thrust, the results showed higher friction coefficient for increasing contact pressure at the thread location (i.e., lower stem diameter or lower pitch).

RESULTS OF POST-MOV TEST ANALYSIS

The deleterious particles test showed that none of the greases tested had scratch counts of 10 or greater. Therefore, no significant large particles were detected in any of the greases tested in the MOV test rig. No significant wear damage occurred during these MOV tests. This is consistent with visual inspections of both stem and nut after each test. Therefore, all greases tested in the MOV rig offered adequate wear protection to both stem and nut contacting surfaces. As a result, no microscope (optical or SEM) inspection of the grease samples was performed.

The results of trace element analysis show that all of the greases picked up zinc, copper, aluminium and iron as a result of MOV testing. This is attributed to slight wear of the stem nut, which is made of C86300 bronze (60% copper, 22-28% zinc, 5-7% aluminium, 2-4% iron and 2% manganese). For most grease candidates, trace element results are within the same order of magnitude after testing in the MOV test rig. Therefore small particle pick-up levels cannot be strongly related to grease performance at the stem/stem nut location.

Dynamics Mechanical Analyzer (DMA) results were shown to be repeatable for grease samples collected following two MOV tests using the same grease. For most greases, the post-test consistency was usually lower than the consistency measured before the MOV test, but this could not be related to grease performance in the MOV test rig. However, for some of the greases tested, there seemed to be a correlation between TST thrust instability measured during the 500 stroke MOV test and significant grease hardening measured with the DMA technique.

RESULTS FOR ACCIDENT CONDITIONS

Effect of high temperature on MOV lubrication characteristics

The OPG nuclear stations requested MOV testing of the best 5-year aged grease candidates under Major Steam Line Break (MSLB) temperature conditions. A temperature profile to cover all OPG MSLB profiles was provided. It consists of increasing the stem/stem nut temperature from 20 to 165°C, maintaining 165°C for 0.5 h, then cooling to 110°C and maintaining that temperature for 7 days before cooling to room temperature. The effect of steam jet and grease washout on stem/stem nut lubrication was not assessed in this study.

A cartridge heater was inserted in the stem to provide heat at the stem/stem nut location. The advantage to using a localized heat source is that the MOVATS cell can be maintained around room-temperature while testing at 165°C at the stem/stem nut location. However, maintaining 165°C at the nut location resulted in extremely high temperatures (>300°C) on the protruding parts of the stem (above and below the nut) because of the greater heat dissipation at the stem/stem nut location. This is not representative of MSLB temperature conditions for which the protruding parts of the stem will only be exposed to a temperature of 165°C. Therefore, the temperature on the lubricated protruding part of the stem (above the nut in opened position, below the nut in closed position) was controlled at 165°C.

The effect of this temperature profile on friction coefficients and TST thrust is shown in Figure 10 for various 5-year aged high-temperature greases. The sensitivity to the temperature profile remained minimal for most 5-year aged greases. Variations of parameters were below 5% for the best case and 10% for most candidates. However there was up to 30% variation in friction coefficient for one grease even though it was a high-temperature grease.

Similar tests were performed for the EDF greases but with a somewhat different high-temperature profile: the greases were slowly heated up to 120°C, then stroked at 120°C before cooling down to room temperature. Increasing temperature, as well as stroking at high temperature, resulted in increased friction coefficients (> 0.15 for most greases tested). However, cooling down to room temperature usually resulted in the return to initial friction coefficient values. For most greases, the variation of friction coefficient was 5-10%.

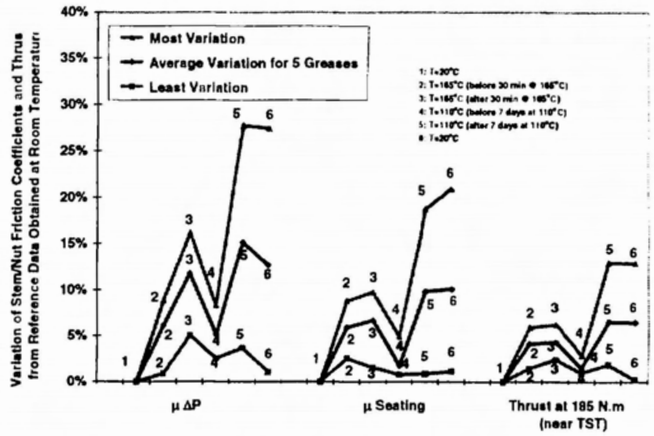

Figure 10: Effect of a Typical OPG MSLB Temperature Profile on Average Friction Coefficients and TST Thrusts.

Effect of high irradiation levels on MOV lubrication characteristics

The best five-year aged greases (best performers in the MOV test rig) were irradiated to a dose of 850 kGy (85 Mrad) to simulate in-service + LOCA + post-LOCA irradiation conditions.

Previous studies showed that, for some greases, properties can be modified by irradiation doses as low as 10 to 100 kGy (1 to 10 Mrad). However, most high quality greases can withstand irradiation doses of up to 1000 kGy (100 Mrad). Beyond 1000 kGy (100 Mrad), most greases are not useable and special products are required [4]. The irradiation level of 850 kGy is just below the threshold value beyond which grease performance can be severely decreased. Therefore, MOV testing of 850 kGy-irradiated greases was requested as part of the grease evaluation process.

The effect of irradiation on friction coefficient and thrust is shown in Figure 11 (comparison over 20 cycles). The change in friction coefficient or thrust as a result of irradiation increase from 100 to 850 kGy is on average 5 to 10%. However, some greases are more affected by irradiation than others (up to 30% variation for one of the greases tested).

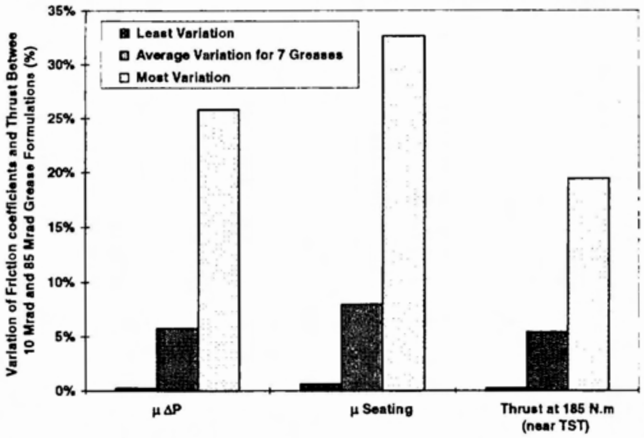

Figure 11: Comparison over 20 cycles of Average Friction Coefficients and TST Thrusts for 10 Mrad and 85 Mrad Grease Formulations).

Additional tests at high temperature using 850 kGy-irradiated greases showed that, for the best candidates, there was no negative combined effect of high temperature and high irradiation level on MOV grease performance.

RECOMMENDATIONS FOR THE SELECTION OF MOV STEM/STEM NUT GREASES

MOV stem/stem nut lubrication is greatly affected by the type of grease used. The following is a set of recommendations to help in choosing suitable lubricants for this specific application. These guidelines are based on test results obtained for more than 30 grease candidates.

A first short list can be drawn up by restricting it to greases that have a suitable consistency for this type of application (usually penetration grades of 1 or 2) and to greases that can be used at temperatures above 150°C.

The resistance to thermal aging should be assessed: following exposure on oven panels at 120°C over 8 weeks, the grease should not have slumped, the change in grease consistency should be less than 2 grades, and the loss in acid buffering capacity should be less than 80% (or TAN limit number of 3).

The grease should be tested in an MOV test rig to derive friction coefficients and assess the resistance to mechanical aging. For best performance, the friction coefficients measured during valve seating for both the unaged and 5-year aged formulations of the grease should be less than 0.15. Grease types combining a synthetic PAO oil and a clay thickener are particularly suitable if a low friction coefficient is required.

Both unaged and 5-year aged formulations of the grease should show adequate resistance to mechanical aging. Ideally, the change in friction coefficients or TST thrust over 250 cycles should be less than 10%, especially if the actuator tripping point is defined using the developed thrust initially measured for a given torque. Grease types combining a mineral oil and a lithium thickener are particularly suitable if parameter stability is required.

Long-term exposure to in-service temperature should have a minimal effect on friction coefficients. For best performance, average friction coefficients measured for the 5-year aged formulation of a grease should not vary by more than 10% from the average value obtained for the unaged formulation.

The grease should also be suitable for high temperature and high irradiation levels that would be typical of accident conditions. The use of high-temperature greases is required in order to guarantee valve operability at peak temperatures of 165°C and accident steady temperatures of 110-120°C. An indication of above average performance at these temperatures is a variation of friction coefficient and TST thrust from reference data measured at room temperature of less than 10%. Some greases combining PAO base oil and clay thickener or mineral oil and lithium complex thickener are suitable for valve stroking at accident temperatures.

CONCLUSION

Standard lubrication tests are not suitable to assess the lubrication performance of greases used at the MOV stem/stem nut location. Specific procedures have been developed by AECL, EDF, and OPG for thermal aging and MOV testing of grease candidates. The assessment also includes MOV grease testing for temperatures and irradiation levels that are typical of accident conditions.

Since a large number of greases were studied, general trends were observed according to the type of grease tested:

- The stem/stem nut friction coefficients measured for the various grease candidates ranged from 0.10 to 0.17. The lowest friction coefficients were found for greases that combine a PAO base oil and a clay thickener.

- The greases that offered the best resistance to mechanical aging (friction coefficient and TST thrust stability with stroke number) combine a mineral oil and a lithium complex thickener. Some of the greases that combine a mineral oil and a calcium complex and greases that contain a polyurea thickener showed poor resistance to mechanical aging.

- The use of EP additives in the grease was not detrimental but did not seem to be absolutely required for optimal stem/stem nut lubrication.

- The five-year aged formulations of the greases were less resistant to mechanical aging than the unaged formulations.

- Most high-temperature greases were suitable for short-term exposure at 165°C and for prolonged exposure at 110-120°C. Several irradiated greases were suitable for stem/stem nut lubrication, even for levels of up to 850 kGy.

Overall, the screening process proved to be successful. From a thermal stability point-of-view, only nine grease candidates out of an initial list of twenty-four were declared suitable for a 5 year regreasing interval. Following testing in the MOV rig, only five of these greases met the majority of requirements for optimal MOV stem/stem nut lubrication (mostly high-temperature greases). Only one grease met these requirements and was also suitable for specific low friction coefficient applications.

ACKNOWLEDGEMENTS

This work was equally funded by the CANDU Owners Group (R&D work package WPIR 0153) and by Electricité de France. The authors would like to acknowledge the contribution to this work of R. Houot, D. Grandison, C. Lade, and D. Pinier.

REFERENCES

1. Gimzewskie, E., 1992, "The Relationship between Oxidation Induction Temperatures and Time for Petroleum Products", Thermochimica Acta, 198.

2. Ito, H., Tomaru, M., Suzuki T., 1988, "Physical and Chemical Aspects of Grease Deterioration in Sealed Ball Bearings", Lubrication Engineering, 44, 10, October.

3. Komatsuzaki, S., Uematsu, T., 1994, "Estimation of Service Life of Grease in Large Size Roller Bearings", Lubrication Engineering, 50, 1, January.

4. Bolt, R., 1995, "Radiation Effects on Lubricants", CANDU Owners Group Lubrication Workshop, Markham, Ontario, Canada.