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CONTINUOUS IMPROVEMENT OF PUMP SEALS[1]

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ABSTRACT

Pump seal reliability continues to be an area needing improvement and ongoing vigilance. Methods have been developed for identifying and assessing factors relating to seal performance, selecting the most relevant ones for a specific station, and then focusing on the most significant aspects and how to improve. Discussion invariably addresses maintenance practices, seal design, monitoring capabilities, operating conditions, transients, and pump and motor design. Success in reliability improvement requires ongoing dialogue among the station operators, pump manufacturers and seal designers.

AECL CAN-seals lead the nuclear industry in reliability and seal life. They effectively save operators millions of dollars in outage time and person-rem. This paper describes some of the significant developments in AECL's ongoing program in seal R&D, as well as recent new installations following the most demanding seal qualification programs to date.

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CONTINUOUS IMPROVEMENT OF PUMP SEALS

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INTRODUCTION

Successful sealing in CANDU® plants requires much more than initial integrity—critical seals must also be optimized for reliability and lifetime if the full benefits of nuclear energy are to be realized. Since the 1970's, AECL has continuously engineered various improvements in the seals of the large primary heat transport (PHT) pumps and smaller pumps such as the shutdown cooling and reactor water cleanup systems of CANDU and BWR power plants.

CAN8 seal development has occurred over a period of three decades, beginning with the development of the CAN2 seal in the 1970's for CANDU PHT pumps. This primary heat transport pump seal was designed to provide better reliability and increased lifetime compared to the seals being used at the time, which were very unreliable. The primary heat transport pumps are the most critical pumps in a plant, causing forced outage time if they fail in service. In the 1980's, further improvements were made to the CAN2 seal for use in older BWR plants with relatively small shafts (5-inch diameter). The operating conditions for these seals are quite severe, in particular because they have to operate for weeks at very low pressure during outages, which challenges the seal's ability to ensure a proper lubricating film between the faces. As the superior performance of these seals was demonstrated in CANDU and US BWRs, efforts to develop a seal for newer BWR plants with larger pumps was initiated. This resulted in the CAN8 seal, first installed at Grand Gulf Nuclear Station in 1992. Around this time, operating conditions at CANDU plants were evolving, with more low-pressure running and other difficult operating conditions. Because their existing seals had difficulty coping with these conditions, the Bruce and Darlington stations have also upgraded to the CAN8 seal. Smaller CAN6 seals were also developed for BWR reactor water cleanup pumps (1990) and CANDU shutdown cooling pumps (1997).

All these "rotary" pump seals are giving excellent service. "Static" elastomer seals such as O-rings are among the many critical aspects of their design and supply. In parallel with pump seal applications, AECL's elastomer expertise has also been applied to static seals for other equipment such as airlocks, where improved inflatable seals are now being installed in a number of CANDU plants.

The benefits of these sealing improvements have been higher reliability, reduced outage time, lower maintenance requirements and rapid payback for the plants adopting them. This paper describes AECL's continuous efforts for improvements in seal technology through an ongoing program of research, development and testing to meet the challenges. Recent programs included testing of pump seals under demanding qualification tests before their retrofit in power stations such as Darlington (1999) and Clinton (2000). CAN8 seals were also recently supplied to Kernkraftwerk Leibstadt, in Switzerland. Installation is expected in summer 2004.

Current work includes rigorous testing and evaluation of new seal materials to maximize seal stability and testing of seal component coating to minimize friction. (High friction between an axial seal and a seal sleeve can significantly alter seal face separation and produce unpredictable leakage or severe seal face rubbing when the shaft moves during pressure or temperature transients.)

Also in progress is a practical method for on-line monitoring of the condition of the seal in terms of seal face wear, which would allow the operator to determine the remaining available life of the seal. This would provide crucial information for inventory, maintenance and outage planning in effective operation of the pump seals.

RECENT SEAL RETROFITS

Until 1999, Darlington NGS had three-stage CAN2 PHT pump seals that had started having various problems, often caused by difficult operating conditions such as low-pressure start-ups. To eliminate these problems, it was decided to upgrade to the newer CAN8 seal design. At the same time, more stringent operating requirements were placed on the seal, such as the ability to survive a prolonged loss of all seal cooling, while still being able to run the pumps. After the new CAN8D seals were installed, previously-existing problems associated with low-pressure operation disappeared, and seal behaviour became much more reliable, effectively eliminating forced outages due to seal failures.

Meanwhile, the Clinton BWR plant in Illinois had been having severe problems with their original equipment reactor recirculation pump seals. These seals routinely leaked much more than expected, often because of erosion grooves cut across the carbon seal face. In 1996 the plant had a very degraded seal that eventually failed suddenly and gave rise to a USNRC investigation and a two-year closure of the plant. AECL was called in shortly after the failure to diagnose the cause and recommend a solution. Clinton accepted the analysis and later decided to convert to CAN8 seals.

The poor performance of the original equipment seals, and the high visibility with the USNRC increased the "pressure" to ensure that the new CAN8C seals performed well. AECL made additional improvements to the CAN8 seal design to handle the specific geometry and operating conditions at Clinton. One finding from the ensuing studies was that the pump shaft was operating very close to its balance point at certain operating conditions, meaning that the shaft could freely move up and down in response to minor perturbations. This likely contributed to many of the seal problems. To address this, AECL designed the replacement seal with a slightly larger sealing diameter, which gave a larger upward hydraulic load on the shaft, forcing it onto the upper motor bearing at normal operating conditions. The seal also has very precise control on the lubricating film thickness between the seal faces. This prevents the faces from rubbing (leading to high wear) while simultaneously maintaining leakage at a low value. Before supplying the final version of the seal to the customer, it was rigorously tested under all postulated transient and normal operating conditions. This effort paid off—the new seals have been performing very well and have eliminated the constant threat of a forced outage.

The following section describes some of the testing that was done to qualify the CAN8 seals for the severe operating conditions at Darlington and Clinton.

PUMP SEAL TESTING AT SEVERE OPERATING CONDITIONS

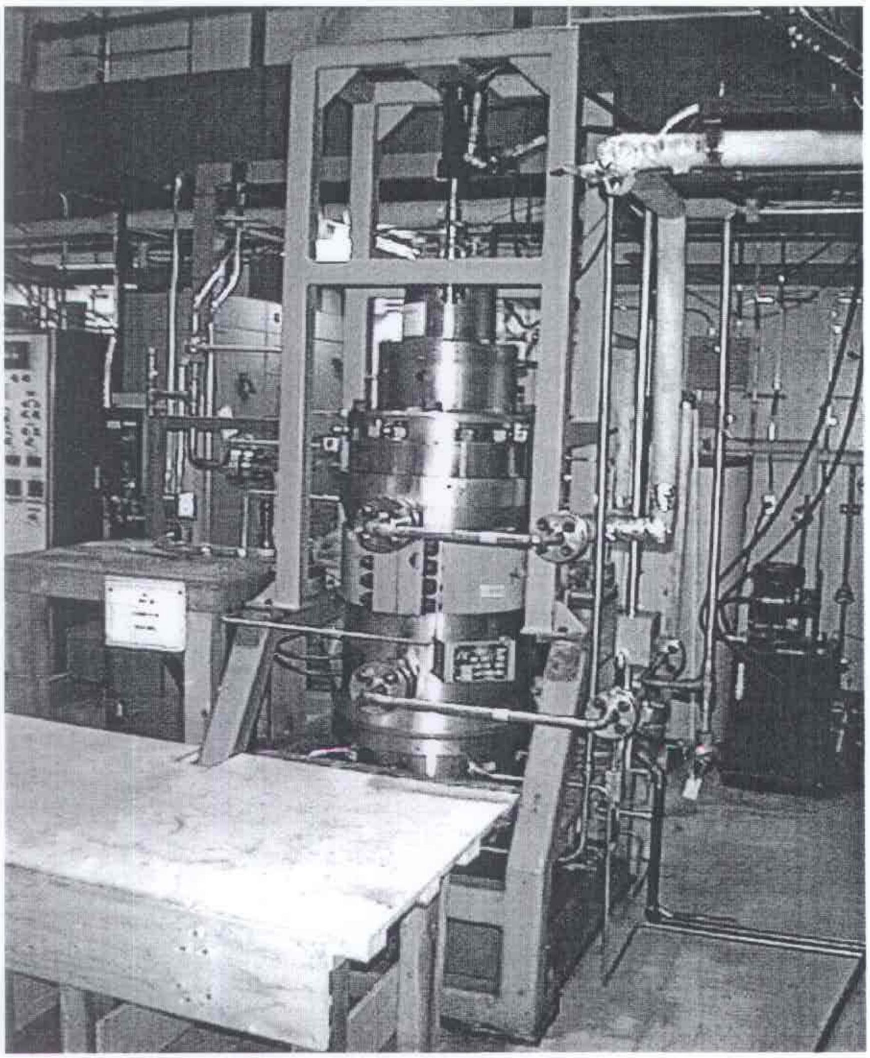

Figure 1: CAN8 Seal Test Rig

The three-stage, 7.375" (0.187 m) size CAN8D seal is a "drop-in" replacement of the CAN2 seal at Darlington NGS. The seal design is similar to the CAN8 seals for Grand Gulf and Bruce stations, with several changes incorporated. The main changes include a live-loaded O-ring instead of a U-cup as the axial sliding seal, a replaceable sleeve insert to facilitate shaft sleeve refurbishments and identical size seals for all the three stages. The changes are intended to improve the seal in low pressure performance and reverse pressure relief capability, and to reduce refurbishment costs. Qualification tests were conducted with the CAN8D seal to simulate the normal PHT pump operating conditions and transients at Darlington using the test rig shown in Figure 1. Other conditions tested were the abnormal or accident conditions, including:

- rapid de-pressurization and reverse pressure (sudden drop in system pressure can momentarily cause a negative pressure drop across a seal stage that can potentially "blow" the seal rings apart causing the seal to de-stage; during testing, system pressure was dropped from 10 MPa to 1 MPa in 0.5 seconds);
- loss of seal injection (seal cavity temperature increased up to 75°C);
- loss of jacket cooling (seal cavity temperature increased up to 105°C).

The CAN8D seal performed very well in the qualification test, meeting all the acceptance criteria including the projected years of service life.

In addition, a test was conducted simulating the loss of both the seal injection and jacket cooling. The system pressure was kept at 10 MPa, rotational speed was 1785 rpm and the seal cavity temperature was raised up to 265°C. The results showed the CAN8D seal functioned effectively throughout the test while sustaining limited damage to the seal components.

The two-stage, 8.000" size CAN8C seal, similar in design but slightly larger than the CAN8D seal, is designed to fit the Reactor Recirculation Pumps (RRP) at the Clinton power station. A 2000-hour qualification test was performed at simulated conditions specific to Clinton. The conditions included normal operations and transient conditions of start-up, shutdown, heat-up, cool-down, flow throttling, and variation of the seal injection flow temperature. Pump shaft motions corresponding to each particular transient, provided by the pump supplier, were imposed onto the test seal. The shaft motions were axial, radial or a combination of axial and radial (tilt). An unusual flow throttling transient was also tested during which the pump shaft "bounced" back and forth axially at 0.25 Hz and 0.25 mm amplitude, for a cumulative total of about 40 hours. The CAN8C seal performed very well throughout these severe test conditions and the acceptance criteria were met.

The CAN8D and CAN8C seals were first installed respectively in 1999 at Darlington NGS and in 2000 at Clinton Power Station, and have been performing well.

Subsequent sections describe some ongoing seal development activities.

DEVELOPMENT TESTING FOR SHAFT SLEEVE IMPROVEMENT

Tests of Elastomer Seal Friction Sliding over a Shaft Sleeve

Shaft seals in nuclear main coolant pumps rely on elastomer seals to provide both axial and angular freedom of movement for the flexibly mounted sealing ring. The axial movement, largely the result of differential thermal expansion and bearing play in pump parts, is characteristically slow and in the range of one to two millimeters. Angular motion, the result of angular misalignment of the face of the rigidly mounted ring relative to the axis of rotation, is at high (shaft) frequency but is an order of magnitude smaller. The friction force transmitted from the shaft sleeve to the flexibly mounted seal ring through its axially sliding elastomer seal, typically either an O-ring or U-cup, must not be enough to drag the seal faces too far open or closed, nor must the elastomer or the sleeve surface wear out or fail to seal in service. Several seal failures have been related to "hang-up" of the seal rings by the elastomer sliding seal because of excessive friction developed during operation. Figure 2 shows the interaction of friction between the seal components.

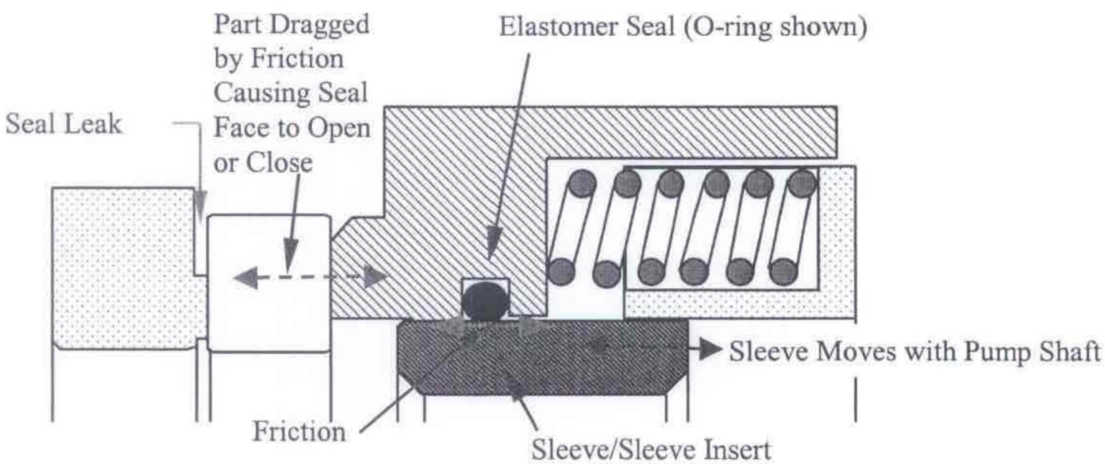

Figure 2: Friction Between Elastomer Seal and Sleeve of a Typical Rotary Seal

As illustration of the effect of a pump shaft moving up or down and dragging the seal faces more closed or open (compared with their nominal separation and leak rate when there is no friction), Figure 3 shows the multiplier effect on leakage for a typical seal due to friction. It is seen to be very sensitive at the negative (opening seal) extreme of friction force where the rapid rise in leak rate may cause seal instability. At the positive (closing seal) extreme of friction force, the drop in leak rate (i.e., reduction in the thickness of the lubricating film between the seal faces) may increase the risk of seal face damage from rubbing. Reduction of the elastomer sliding friction thus improves seal performance. To achieve this, tests were conducted to compare and evaluate the sliding friction between the axial elastomer seal and the shaft sleeves made from a selection of materials including some with hard surface coatings.

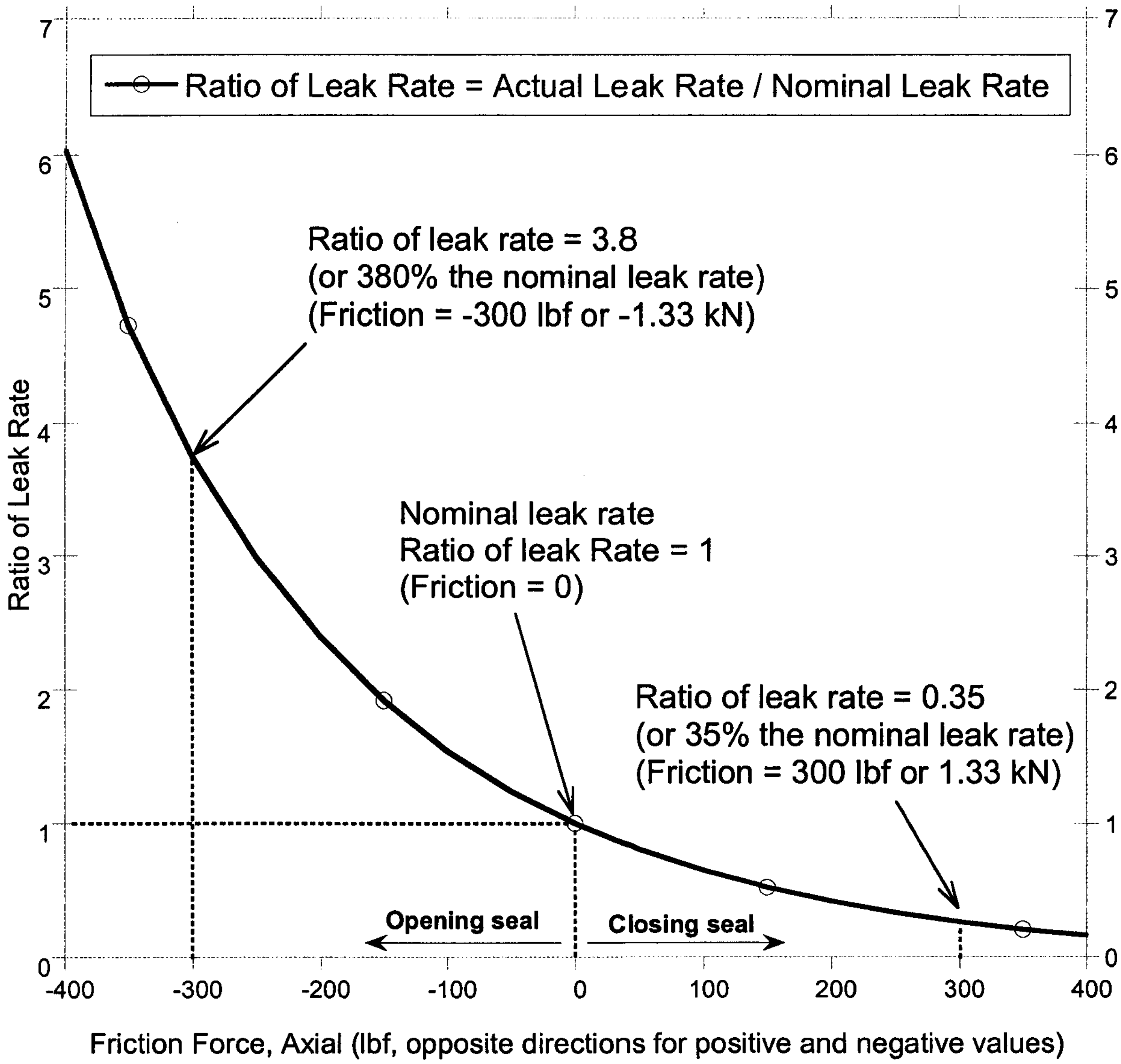

Figure 3: Ratios of Leak Rate vs. Friction Force

The friction for U-cups was known from earlier testing to be marginally higher than for O-rings. The earlier version of the CAN8 seal uses U-cups as the axial seals, while the latter versions (CAN8C and CAN8D) use O-rings.

In the CAN8 seal improvement program, friction tests were conducted for both U-cups and O-rings, sliding against shaft sleeves. Various materials and surface coatings were used on the shaft sleeves. Push-pull tests were performed to measure friction of pairs of either U-cups or O-rings for a range of movements and conditions representative of pump operation at the power stations. The tests were conducted in a sliding seal friction tester with a vertically mounted shaft driven by a hydraulic system for controlled reciprocating movements. The tester was supplied with de-mineralized water at controlled pressures. Figure 4 shows the arrangement of the seal friction tester. Among the various sleeve materials tested, of particular interest were the chrome oxide coated sleeves, similar to those in use at the Bruce station. Interestingly, with lightly-lubricated seals, the sleeve material was found not to be as significant as the elastomer material. EPDM was found to give about 25% lower friction than nitrile.

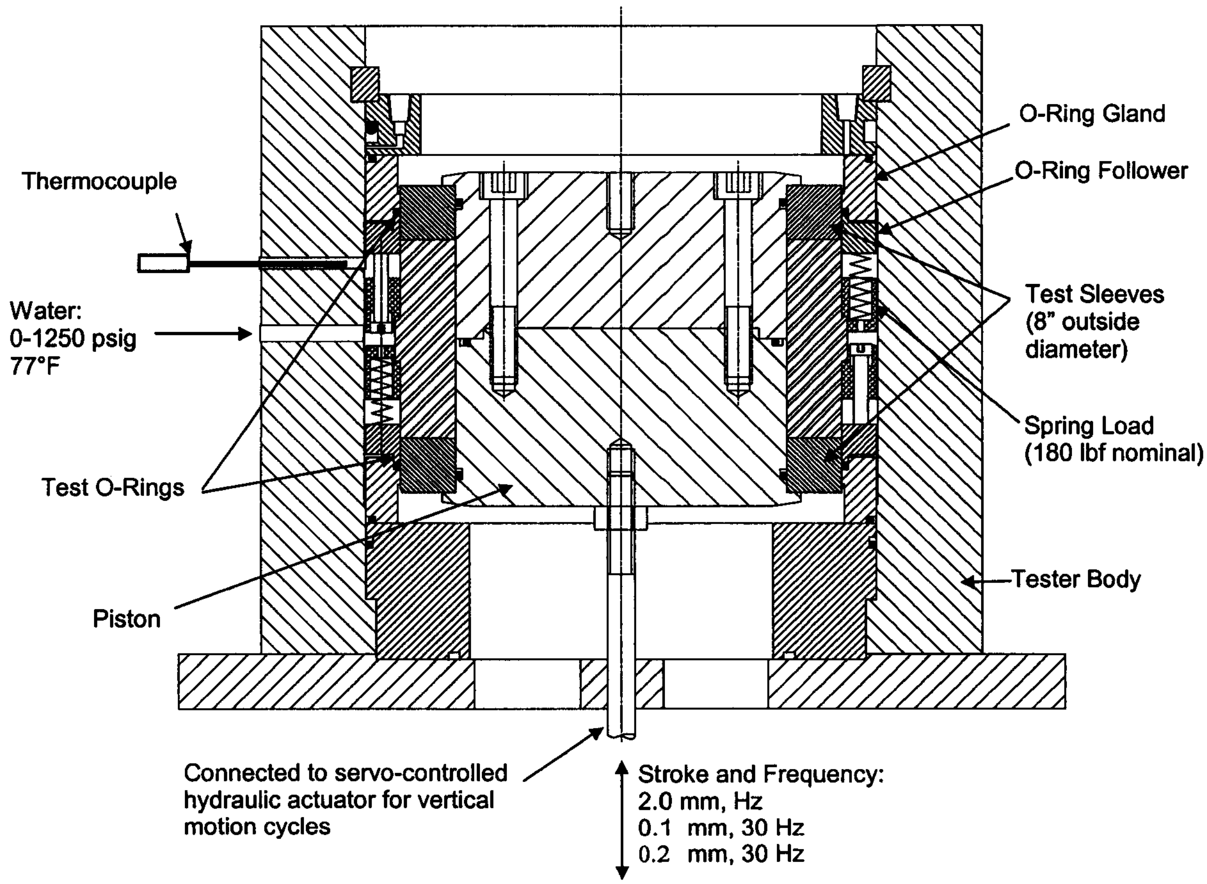

Figure 4: Sliding Seal Friction Tester

Figure 5 shows the friction for unlubricated 5.33 mm (0.210") cross-section EPDM O-rings on 7" diameter shaft sleeves. The two types of chrome oxide coated sleeves produced the highest friction, while the 410 SS and 17-4 PH produced much lower friction. Chrome oxide has clear advantages for improving wear resistance, however it was seen that the application process and surface finish are critical to ensuring that friction is not excessive. The process used by Bruce Power (labeled CMF in Figure 5) minimizes the chrome oxide friction while maintaining its superior wear qualities. Other chrome oxide coatings with rougher surface finish can cause serious performance problems. AECL is currently investigating other sleeve materials in an effort to achieve still lower friction and excellent wear resistance.

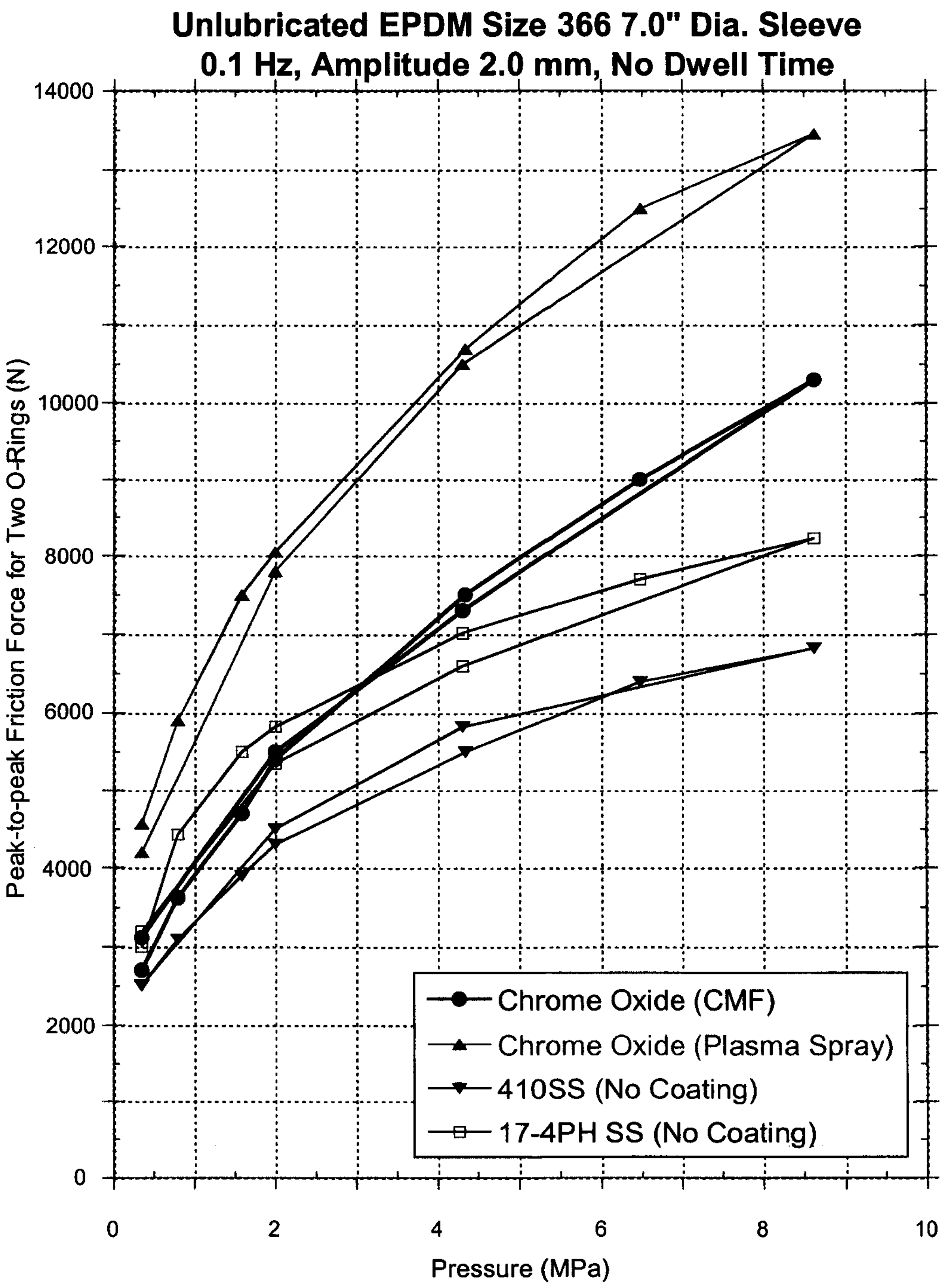

Figure 5: Friction of Unlubricated 7" Size 0.210" Cross-Section EPDM O-Ring

Wear Resistance Tests

Similar sliding tests were conducted to compare wear resistance of various materials. Reciprocating axial motion was imposed on the shaft at frequencies of 15 to 40 Hz, with amplitudes of up to ±11 mm, while the seal was pressurized at normal operating pressure. As expected, lubrication reduced wear, harder surfaces had lower wear, and similar metals tended to suffer from adhesive pick-up between the sleeve and the elastomer holder.

Discussion of Friction and Wear Test Results

Significant improvement in seal performance can be achieved by optimizing the mating materials used for shaft sleeve sliding surfaces. It is usually the "solid" surface, rather than the elastomer, that wears as a result of continuous axial shaft motion. Choosing hard materials that wear well for surfaces in contact with the sliding elastomer seal can therefore maximize lifetime. Softer surfaces may be damaged more easily and may lead to shorter lifetime, depending on the amount of shaft motion.

In choosing the sleeve material, it is important to minimize friction as well as wear. An example of the importance of friction occurred a number of years ago when the Bruce station used a few sleeves from a different supplier that provided a much rougher chrome oxide surface finish, and consequently a significantly higher sliding friction. This problem, combined with the fact that the pump shaft was almost balanced under some operating conditions (similar to the Clinton station), led to "interesting" shaft instability. A feedback oscillation started where friction from vertical shaft motion changed seal leakage enough to affect the pressure breakdown between the two stages, which changed the vertical load on the shaft enough to cause more shaft motion. This problem completely disappeared when these sleeves were replaced with lower friction sleeves (coated at their own shop) during the next scheduled outage.

WEAR MONITOR FOR FUTURE SEALS

During operation of mechanical face seals, the carbon stator seal surface rubbing against the harder carbide rotor slowly wears away, as intended. Typically, the seal can be used safely until the total wear exceeds a pre-determined amount, after which a new stator is required. However, during operation, it is currently not possible to determine the amount of wear. Therefore, the decision about when to replace the seal is based on many other factors, including the total operating time, time until the next plant outage, seal performance (interstage pressure, leakage, temperature), historical performance of similar seals, and the number and severity of system transients to which the seal has been exposed.

One potential method for on-line seal wear monitoring has been evaluated in small-scale tests at AECL's Chalk River Laboratories. This technique makes use of the fact that, for flow exiting a tube towards a flat surface, the distance between the tube exit and the flat surface affects the pressure required to maintain a given flow in the tube. In theory, the pressure differential depends on the square of the separation. If a seal is designed so that the separation between the tube and plate changes as the amount of material worn off the carbon seal face changes, then the amount of wear can be inferred by measuring the pressure or flow in the tube.

If the tube diameter and initial gap are chosen to be of the same order of magnitude as the seal face height, the device will be quite sensitive. As gap tends towards zero due to seal face wear, pressure differential and hence the monitored signal increases as a power function.

Simple laboratory tests were performed using the setup shown in Figure 6 to explore the possibility of using this technique for seal wear measurements and to determine practical limits for the technique. Tests were performed in both stationary and rotating configurations. The effects on the pressure differential of flow rate, distance from the tube exit to the flat surface, and seal rotational speed were investigated.

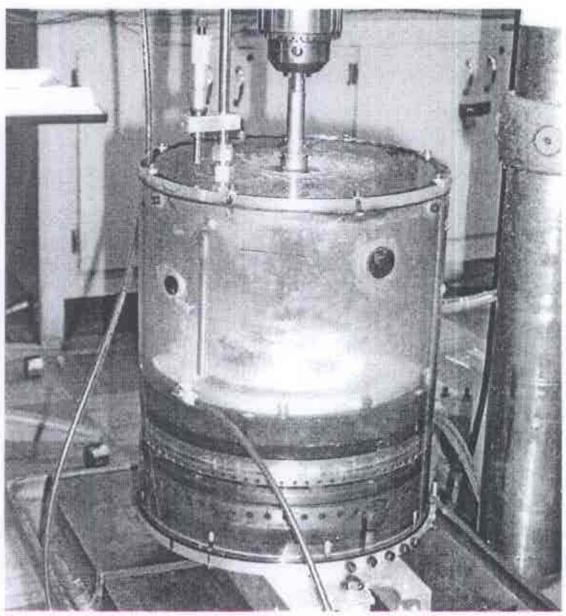

Figure 6: Experimental Setup for Wear Monitor Testing

It was found that the device had reasonable sensitivity to face wear, but sensitivity was reduced at higher rotational speeds, probably due to the water flowing past the end of the tube "sucking" water out of the tube due to the venturi effect. This is a practical complication to be considered in the final wear monitor design. The major practical consideration, however, is that additional instrumentation would be required to measure the pressure. In spite of the difficulties, this remains a goal for future applications of AECL pump seals.

SUMMARY

Over the past several years, continued development of AECL CAN-seals has led to increased reliability, even under very challenging operating conditions. Seals have been installed in over 100 nuclear pumps and are providing significant savings in operating costs to customers compared to previous seals. Each new application is supported by rigorous testing designed to cover the entire spectrum of operating conditions, including normal and accident conditions.

AECL continues to refine its seal products through its research and development programs. Current areas of focus include reducing shaft sleeve friction and on-line monitoring. In addition, AECL's ongoing product support permits users to address specific issues as they arise.