WHEN TO REPLACE A REACTOR COOLANT PUMP SEAL

by

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Abstract

The prime objectives of a seal maintenance strategy for the main reactor coolant pumps of nuclear plants are to avoid spills and forced outages, while minimizing maintenance costs and radiation exposure. Reactor coolant pump seals in early nuclear plants were replaced every fuelling outage, if not sooner! With steadily improving reliability it has become more difficult to decide when to replace a seal. This paper describes tools to help these decisions.

Seals can be defined as operating either normally, deteriorated, or failed. These "conditions" can be defined in terms of measured temperatures and leakages (and/or interseal pressures). Recent guidelines and charts based on these parameters, and the ways they are adapted for two- and three-stage cartridges, are described.

A further consideration is the type of failure. The most common modes are presented, with their causes and their impact (sudden or gradual) on seal performance. Based on identification of these failure modes and an assessment of the percentage remaining life, a replacement strategy is described.

A final issue is service life of the elastomers used in pump seals. These degrade with age and exposure to heat, radiation, stress, and other environmental factors or contaminants (in service, or simply sitting on the shelf). Recommendations are presented based on hardness and compression set aging data for elastomers used in CAN-seals for reactor coolant pumps in the US and in the Bruce and Darlington nuclear plants.

INTRODUCTION

The prime objectives of a seal maintenance strategy for the main reactor coolant pumps of nuclear plants are first, to avoid spills, and second, to avoid forced outages. Other significant objectives are to minimize maintenance costs and radiation exposure.

In many early light-water cooled plants it was easy to decide when to replace their reactor coolant pump seals—every fuelling outage! Early CANDU® plants began with similarly frequent seal replacements [Ref. 1]. However, seals now need to be replaced less often because their reliability has been improved [2]. This makes choosing the best time for replacement much more difficult.

Other than reacting to obvious seal failures with a mandatory "stop and replace," plant staff can choose to make more logical seal replacement decisions. There are two types of judgments called for. One concerns seals that continue to perform normally but are known to be aging and becoming more likely to fail; the other concerns seals that are showing symptoms of deterioration but have not (yet) failed and may therefore safely be kept running.

The biggest unknown for "normal" seals is their lifetime probability distribution. Seals are not unlike people in this regard. The old and the young have a higher probability of dying than those in the middle. Up to a certain age, therefore, it is a better bet (for avoiding failures) not to replace a seal that is behaving normally. The question is, "Until what age?"

For a seal showing symptoms of "sickness" the questions become, "How quickly will it deteriorate?" and, "Will it fail gradually/safely or suddenly/catastrophically?"

TYPICAL REACTOR COOLANT PUMP SEAL

CANDU® plants, like other water-cooled reactors, have large pumps that circulate the primary heat transport system water (reactor coolant) [3]. These typically have multi-stage shaft seals (Figure 1) that are located in a "stuffing-box" cooled by various means: component cooling water (CCW) jacket; partial recirculation of system water through an external cooler; and usually a clean, cool injection (purge) flow from some independent high pressure source.

The seals are typically arranged in a multi-stage cartridge for easy maintenance and to boost the reliability of a single stage. In Pickering and Bruce [4], the arrangement is two face seals backed up by a close clearance bushing, as is typical in Boiling Water Reactors (BWRs) (Figure 1). In the later CANDU® plants, three face seals are used, as is typical in Pressurized Water Reactors (PWRs) (Figure 2). The face seals normally share the pressure drop, but are designed for full pressure capability should the other stage(s) fail. The sharing is governed by a "staging flow" that is bled around each stage, typically 3 to 7 L/min passing through small bore tubing integral to the cartridge.

Typical monitoring of a two-stage cartridge is depicted in Figure 1, showing pressure (P), temperature (T) and flow (FS), with high (HI) and low (LO) alarms as indicated. For a three-stage cartridge, one further item is monitored: the other interseal pressure. These monitored parameters are essentially the only means for plant staff to diagnose the health of a seal cartridge [5].

SYMPTOMS OF IMPENDING FAILURE

Considering "sick" seals first, plant operators need to have as clear instructions as possible on how to proceed. This is because the "expert" (seal designer or system engineer) is at work only one hour in five, while plants run around the clock. Seals can be defined as operating either "normally," "deteriorated," or "failed." These can be defined in terms of measured temperatures and leakages (and/or interseal pressures).

Temperature Symptoms

Considering temperature, this is normally monitored where the water flows into or out of the seal cartridge. It may increase because of (i) some externally driven event such as loss of seal cooling, or (ii) through friction generated by the seals themselves [6].

Whatever the cause of high temperature, the elastomers are at risk of aging prematurely. However, the seal integrity is much less threatened when known external events are the cause and the seal faces are known to have been running normally at the start of the "event."

Temperature guidelines, therefore, need to reflect this difference in scenarios. If a CAN-seal is generating the extra heat itself, typical guidelines provided by AECL are based on the power that goes into heating the water. For example, a CAN8C seal, 203 mm diameter, 1800 rpm, sealing warm water at 7 MPa, broken down across two stages by a staging flow of 3.8 L/min, is defined to have a "deteriorated" upper stage if the staging flow around this stage picks up more than 15.2°C. Similarly, this stage is defined as "failed" if the temperature increase is more than twice this. These increases correspond to 4 kW of frictional heating for "deteriorated" and 8 kW for "failed." The temperature guidelines for this seal are depicted in Figure 3 (at left), including "soft" guidelines for the lower stage based on heating above CCW temperature, Tc. For seals of other types, sizes or cooling circuitry, these guidelines must be adjusted.

When it is known that a CAN-seal is not self-heating in any abnormal way, the guidelines are typically more relaxed. For example, for CAN-seals with nitrile U-cups it is recommend to shut off and not restart a pump if the seal region exceeds 95°C for more than 10 hours, or 120°C at any time. For all other CAN-seals (some of which have nitrile O-rings but not nitrile U-cups) the guidelines are further relaxed to 2 hours at 120°C, or 140°C at any time, depicted for the CAN8C seal in Figure 3 (at top right).

These criteria give a comfortable margin against elastomer damage, as can be seen from the data in Table 2, discussed later. However, they allow for the fact that the actual temperature of some of the elastomer parts, especially those nearest the seal faces, will be more than the monitored temperatures, since bulk water in the seal cavities is what is measured. Also, they recognize that high temperature, even when known to be precipitated externally, will mask any subsequent increase in seal friction and is therefore risky to allow for very long.

Leakage and Pressure Symptoms

Since it is clear to everyone that a seal is failed when it is leaking excessively, leakage should be monitored frequently and trends watched carefully. This is easier said than done. Plants typically have sightglasses to "go see" what is issuing from the back end of a seal cartridge. There are also various excess flow alarms to sense when it is too much! Interseal pressures are much easier to measure with a resolution sufficient to detect the fractions of a L/min typically of interest with seals. Operators, therefore, need guidelines based on these pressures (and the "back-end" leakage) to tell them whether everything is "normal"—or whether one or more stages in the seal cartridge is leaking enough to be defined as "failed;" or an intermediate amount defined as "deteriorated."

This is simpler for a two-stage cartridge than for three. One "Seal Condition Map" (Figure 4) allows its condition (based on leakage and pressure drop) to be monitored according to where it is and where it's going on the "map." The horizontal axis is the interseal pressure, P2, as a ratio of system pressure, P1. The vertical axis is upper stage seal leakage plus staging flow. Figure 4 assumes equal staging coils giving flow versus pressure that follows the curve shown in L/min at 7 MPa system pressure. This flow can therefore be read directly from Figure 4; a measured value is not needed. Upper (i.e., No. 2) stage leakage must be measured and added to it to give the value of total outleakage.

As indicated (Figure 4), "normal" condition is shown by the light grey area in the middle of the map. Based on experience, AECL chooses to define a seal stage as "deteriorated" when it leaks more than a certain amount. For the CAN2A seal depicted in Figure 4, with normal staging of 3.5 / 7 MPa, the map shows both stages leaking about 1 L/min when just "deteriorated." If only one stage leaks, the pressure staging is about 60%-40% when that stage is defined as just "deteriorated." A stage is similarly defined on the map (Figure 4) as "failed" when it de-stages to about 90%-10%, as shown by the vertical boundaries of the black areas, or the combined outleakage exceeds 5.6 L/min, the horizontal boundary.

The x-axis is non-dimensionalized to enable it to be used for other pressures, but the y-axis is for the normal system pressure of 7 MPa. For very low system pressures the deterioration and failure criteria should be relaxed, as described later for a three-stage cartridge.

In the event of failure of one stage of a two-stage cartridge, the remaining stage is designed to handle full system pressure differential without a serious loss of remaining lifetime. However, the margin of backup is reduced. With one "failed" stage, and all pressure across the one remaining stage, the close-clearance bushing above the seal cartridge provides the only backup.

For the three-stage CAN8D seal cartridge supplied for Darlington main pumps [7], more complex seal condition maps were needed. These are shown in Figure 5 for three values of upper stage leakage, at 10 MPa system pressure. These "maps" show condition of the lower and middle seal stages (based on their leakage and the pressure drop across them) as calculated from the two (monitored) interseal pressures. All maps are for equal staging coils.

As indicated on the maps, a "deteriorated" seal stage is defined in this case by AECL as having more than 0.3 L/min leakage per MPa of pressure drop across it (i.e., 1 L/min for normal staging of 3.33 MPa). A stage is correspondingly defined as "failed" when it reaches 1.5 L/min/MPa (i.e., 5 L/min, or about 1.2 gpm, for normal staging pressure). "Normal" condition, as shown by the cross-hatched area on the maps, refers to the lower and middle seal stages only, not the upper stage. The condition of the upper stage derives from upper interseal pressure and upper stage leakage ("back-end" of the cartridge), which *must* be measured, or reasonably estimated from a sightglass, or other reading. This is because not only does it identify whether the upper stage is "deteriorated" or "failed," but it also tells which map is the appropriate one to use to determine the condition of the lower and middle stages. If actual upper interseal pressure is lower than covered by one or another map, it is probably because upper stage leakage is more than that map is plotted for. For example, if upper interseal pressure is less than 2.6 MPa, upper stage leakage must be more than 1 L/min (see Figure 5b).

The maps show that the wrong conclusion regarding condition of the lower and middle stages would come from using the wrong map.

Each map is conservative if used when actual leakage is less than the value it is drawn for, i.e., it may predict the lower and middle stages to be failed or deteriorated, when in fact they are not.

For system pressures lower than 10 MPa, it is again recommended to relax the deterioration and failure criteria in proportion to the pressure, the rationale being that (i) at lower pressure the consequences of seal failure (potential for spill) are proportionately less, and (ii) the seal is naturally less stable because of the greater influence of forces other than pressure.

In the event of failure of one or two stages of a three-stage cartridge, the remaining stage(s) will again handle full system pressure differential without serious loss of remaining lifetime. With one "failed" stage, the cartridge still has the backup inherent in a two-stage cartridge. With two stages "failed" and all pressure across the one remaining stage, the bushing above the cartridge again provides the only backup.

TYPES OF FAILURE

A further consideration is the type of failure [3] at risk with "sick" or "old" seals. If this can be diagnosed, it can be used in decision-making about when to schedule replacement. There are many modes of failures and causes for them. Many are design-related and can be ignored if the design in question is already proven to give acceptable lifetime for the expected operating conditions. Table 1 lists the remaining causes.

The boxes show whether each cause is unlikely to lead to each mode of failure, or whether failures would be gradual or sudden. If the probability of sudden failure can be ruled out by knowing what causes exist or have existed, and what symptoms have been observed, it becomes much less risky to continue running. This points to the benefits of collecting and using data on seal deterioration and failure modes / frequencies, as described in the next section.

RELIABILITY-BASED SEAL REPLACEMENT

Considering normally behaving seals next, there is often scant data from which to derive a seal lifetime probability distribution. The population of seals is small, there are many design differences, they are subjected to different conditions in different plants, and few are allowed to serve long enough to fail. For a new plant or application there may truly be <u>no</u> relevant data, in which case the first maintenance strategy is to generate some!

The strategy for doing this without suffering undue failures is to identify significant failure modes and, where possible, to assess the percentage lifetime used up by non-failed seals. This requires inspecting them carefully when they are removed for preventative maintenance. Probabilities of failure in the next increment of time can then be calculated using this data, factoring-in the obvious information that currently operating seals have not failed up to their current "age."

As the starting point for a design being newly introduced to a plant, at least one seal should be taken out early—not left beyond its target design lifetime. If in good condition, this allows the next preventative replacement to be deferred, and so on, with increasing confidence in the decisions. Eventually enough data exists to be very confident when to take a "good old-un" out of service. This is the situation that has been cultivated with the CAN2A seal.

PREDICTIVE MAINTENANCE—CAN2A

The CAN2A two-stage seal cartridge, a forerunner of the CAN8 design, is installed in twelve pumps in three BWRs [8]. A predictive maintenance strategy has been well developed in their fifteen years of use.

Service Data

All CAN2A seal service data is summarized in Figure 6, showing dates of installation and replacement, including reasons and, generally, the amounts of wear. Of the thirty installations to date, there have been eighteen replacements, classified as follows:

No. of Seals	Seal-Related Reason for Replacement
8	No seal-related reason—seal performing normally.
2	Unknown.
3	Sleeve and U-cup deterioration
4	Unusual (out-of-specification) operating conditions.
1	"Infant mortality" (faulty maintenance).

From detailed inspections, there is extensive, quantitative data on carbon seal face wear, with qualitative data also for deterioration of all other seal parts. No CAN2A seals have worn out, and at least half the eighteen seal cartridges replaced to date had no other significant damage.

Data and probabilities for each of the actual and potential failure modes are now described.

Failure Probability—Carbon Face Wearout

Of the eighteen replacements (Figure 6), only thirteen were relevant for predicting carbon face lifetime. (Not used were those with less than six months running time, or uncertain wear.) From the data for these twenty-six stages, assuming constant rate of wear, the following probabilities of failure were calculated:

Years	0-5	5-10	10-15	15-20	20+
No. with end of life during each 5-year period.	0	1	1	7	17
P_c, per stage	0%	4%	4%	29%	100%
P_c, for either stage of two-stage cartridge	0%	8%	8%	50%	100%

Conditional probability, P_c, is for a surviving seal to wear out in the next five-year period. The probability of failure for a two-stage cartridge is higher because wearout of either one, considered independently, would cause failure of the cartridge. From these probabilities it is seen that carbon face wearout is an unlikely failure mode until 15-20 years.

Failure Probability—Sleeve & U-Cup

There have been three occurrences of de-staging because of deterioration of a sleeve or U-cup, causing seal replacements after 4, 8 and 10 years. Failure probabilities derived from this, and similarly for other failure modes, are given later under "Combined Probabilities." Since there is no data beyond 10 years operating lifetime, any further extrapolation is speculative.

Failure Probability—Unusual Operating Conditions

Erosion of the rear of the carbon, apparently caused by the excessive dirt found in the seal (from the reactor coolant system), progressed far enough that two cartridges were replaced recently. This type of failure appears to correlate with particularly dirty water rather than operating time, hence the "unusual conditions" classification.

Another unusual occurrence that caused failure of a seal in 1993 was an essentially instantaneous depressurization of the reactor coolant system during cold testing—a mistake by operations staff. This displaced a U-cup.

In 1999, a cartridge ran overheated for at least four months through loss of external cooling—something the seal was never designed to withstand. The nitrile upper stage U-cup hardened such that the cartridge de-staged.

Based on the assumed random occurrence of these unusual operating conditions, which historically have required four CAN2A seal replacements in about 110 pump-years, the conclusion is a 3.6% annual probability of this type of failure in each pump. The conditional probability that a seal cartridge will fail by this mode during its next five years is 17%, independent of its age. For the first 10 years, this is the dominant failure mode.

Failure Probability—Infant Mortality

This type of failure occurs soon after re-start with a replacement seal that has been improperly assembled or installed, has faulty parts, or other problems associated with the change-out. This has happened once in thirty seal installations. Its probability is therefore 3% in the first year, and zero subsequently.

Combined Probabilities

Based on the preceding information, the conditional probabilities for a CAN2A seal to fail during its next five year operating period due to various causes are summarized as follows.

Cause \ Years	0-5	5-10	10-15	15-20	20+
Carbon Wear	0%	8%	8%	50%	100%
Sleeve & U-Cup	8%	18%	25%	25%	100%
Operating Conditions	17%	17%	17%	17%	100%
Infant Mortality	3%	0%	0%	0%	0%
P_c, Total	**26%**	**37%**	**43%**	**69%**	**100%**

When to Replace?

Between the fifth and tenth year the annual probability of failure increases from roughly 6% to 9%, then further to about 14% by the fifteenth year. Knowledge of the numbers provides the previously missing half of the information required for best preventative maintenance decisions. The other half involves the costs and dose for a "convenient" seal replacement (during an outage) versus one that is not (because it forces an outage).

The probabilities derived from Plants A and B do not necessarily apply to Plant C (Figure 6). In this case, the CAN2A seal was modified slightly because the pumps in Plant C run at higher speed, among other operating differences. However, much remains the same as in Plants A and B. The most reasonable strategy is to weight the data according to the similarities and differences. For example, while no seal inspection or failure data yet exists from Plant C, Plant A and B data is being used uncorrected. As Plant C data grows, it will be factored in with several times the weighting.

CAN8 seal introductions have similarly depended for their starting data on previous CAN-seal experience, with four different versions of similar heritage now having been installed: CAN8A & B in Bruce, CAN8C for BWR, and CAN8D in Darlington. Data from Bruce is by far the most extensive.

ELASTOMER AGING

A final issue affecting pump seals is life of the elastomers [9]. These degrade with age and exposure to heat, radiation, stress, and other environmental factors or contaminants. They cannot be left in service indefinitely, or even on the shelf, without eventually failing. The age at which they fail, however, is usually beyond the normal replacement interval for reactor coolant pump seals unless temperature is unusually high.

Elastomers are used for the O-rings, U-cup seals and drive belts in CAN-seals. They are individually packaged and provided with an Information Sheet (example in Figure 7) giving cure date and "install before" dates for normal or refrigerated storage. These "shelf lives" are based on several principles, (i) extrapolations from accelerated aging test data should be conservative and not be extrapolated beyond 10 years without back-up data from the field, (ii) shelf life should not "use up" more than 10% of the potential service life of a new part, (iii) shelf life beyond about ten years is of dubious value to the user, and (iv) new EPDM parts should not fail in 10 years of normal service at up to 75°C (~160°F), including 20 Mrad radiation exposure (9 years after end of shelf life)—this time being generally sufficient to avoid replacing a seal cartridge simply through expiry of an elastomer part.

The user is dependent on the seal supplier for this elastomer-specific information regarding aging. It then needs to be factored into the seal maintenance strategy, especially for excessive service temperatures or radiation exposures, and for any nitrile materials used.

When a CAN-seal cartridge is replaced, the recommendation is to replace all the elastomer parts. This is not because they all wear or degrade at the same rate and none is ever re-usable. It is because they are relatively inexpensive, easily damaged, difficult to identify and trace, and all degrade somewhat in service compared with new. It is therefore fruitless to declare any elastomer part to have a longer service life than the "weakest link" in a cartridge, although longer shelf life is helpful.

Failure Modes and Values for Elastomer Parts

Only bore-type elastomer seals have significant potential for failing, thus cutting short the service life of the CAN-seal cartridge containing them. Face-type O-rings leak very little when they fail, and drive belts in CAN-seals still function effectively even if broken or severely hardened.

The most reasonable failure mode for non-spring-loaded, bore-type seals is loss of sealing force through compression set. In static situations, 75% set is used as the most reasonable failure criterion. Extrusion is not an aging-type failure and is avoided in CAN-seals by appropriate design and material quality control. Chemical attack may occur, but only if the seal environment is contaminated. Similar comments rule out other conceivable failures such as explosive decompression or mechanical breakage.

The axially sliding, bore-type O-rings and U-cups that accommodate shaft axial movement (axial seals) are most at risk. Wear may occur, but testing has shown it will not be life-limiting if misalignment, shaft vibration and contamination are normal and within specifications. These seals are live-loaded by springs in CAN seals, and are therefore not susceptible to failure by compression set. Their most likely failure mode is to become too hard to seal against scratches and undulations in the sleeve surface they must slide over, or too inflexible to keep contact with the sleeve during temperature variations. Shore A (Durometer) hardness greater than 90 is therefore used as the most reasonable failure criterion.

Age-Related Data for Elastomers in CAN Seals

The elastomers used in CAN seals are from a select group of compounds for which AECL has generated extensive aging data. This is summarized in Table 2. The EPDMs all have 10 years shelf life, (or 20 years refrigerated), with subsequent service life of 9 years at 85°C. For lower temperatures, and considering that air may be the environment rather than water, a conservative extrapolation of the data is that the rate of aging halves for every 20°C below 85°C; hence 18 years service life at 65°C (150°F). For higher temperatures, it is conservative to extrapolate that the rate of aging doubles every 10°C above 85°C; hence 4-1/2 years at 95°C.

Nitriles are only used where there is risk of contamination by oil. This is because the data shows them to be much more limited in their high temperature performance, as detailed in Table 2.

These shelf and service lives assume there are no additional sources of deterioration. The stored parts must be kept in opaque plastic bags in an atmosphere free of contaminants such as ozone and oil vapours. The in-service water must meet the normal chemical and other requirements for nuclear plants, and the dimensional, runout and alignment specifications for the seal must be met.

CONCLUSION

The elements of a comprehensive preventative maintenance strategy for reactor coolant pump seals have been presented, along with the tools to implement it. Examples relate to AECL's CAN2A and CAN8 seals, to two-stage and three-stage cartridges, and to seals showing symptoms of deterioration or not. The principles apply readily to other seals. They help users to make the best decisions about when to replace reactor coolant pump seals—those running normally and those showing signs of deterioration. If the best decisions are made, then the overall results will be for the best, even if the consequences in a few isolated cases are not.

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REFERENCES

1. Burchett, P.R. and Metcalfe, R., "Primary Heat Transport Pump Seal Reliability Performance and Development," 14th Inter-RAM Conf. for the Electric Power Industry, May 1987.

2. Metcalfe, R., "Developing Reliable and Safe Reactor Coolant Pump Seals," 4th Intl. Workshop on Main Coolant Pumps, Electric Power Research Institute, Palo Alto, USA, April 1991.

3. Huber, K.A., Darling, D.B. and Korf, M.A., "A Reliability-Centred Maintenance Program for Primary Reactor Pumps," 4th Intl. Workshop on Main Coolant Pumps, Electric Power Research Institute, Palo Alto, USA, April 1991.

4. Graham, T., McInnes, D. and Rhodes, D., "Improved Operation in CANDU® Plants with CAN8 PHT Pump Seals," 4th Intl. Conf. on CANDU Maintenance, Canadian Nuclear Society, Toronto, Nov. 1997.

5. Graham, T., Metcalfe, R., Rhodes, D. and McInnes, D.,"Improving Primary Heat Transport Pump Seals" 3rd Intl. Conf. on CANDU Maintenance, Canadian Nuclear Society, Toronto, Nov. 1995.

6. Luckas, W.J., Ruger, C.J. and Tingle, A.G., "Reactor Coolant Pump Seal Related Instrumentation and Operator Response: An Evaluation of Adequacy to Anticipate Potential Seal Failures," Brookhaven National Lab., NY, Report FIN A-3806, prepared for US-NRC, 1985.

7. Graham, T. Metcalfe, R. and Burchett, P., "Reactor Coolant Pump Seal Response to Loss of Cooling," 16th Intl. Conf. on Fluid Sealing, BHR Group, Cranfield, Sept. 2000.

8. Metcalfe, R., Rhodes, D. and Peterson, A., "Development of a Nuclear Pump Seal for BWR Application," 4th Intl. Workshop on Main Coolant Pumps, Electric Power Research Institute, Palo Alto, USA, April 1991.

9. Wensel, R. and Wittich. K., "Improved Reliability, Maintainability and Safety through Elastomer Upgrading," 3rd Intl. Conf. on CANDU Maintenance, Canadian Nuclear Society, Toronto, Nov. 1995.

Table 1: Pump Seal Cartridge Failure Modes and Their Potential Causes

MODE / CAUSE	Part Breakage	Carbon Wear	Erosion or Corrosion	Sleeve Wear	Axial Seal Extrusion or Binding	Other Elastomer Degradation
Old Age	Unlikely	Gradual	Gradual	Gradual	Sudden	Gradual
Over- or Under-Pressure	Unlikely	Gradual	Unlikely	Unlikely	Sudden	Sudden
Over-Temp.	Sudden	Sudden	Gradual	Unlikely	Unlikely	Gradual
Thermal Shock	Sudden	Unlikely	Unlikely	Unlikely	Unlikely	Unlikely
Shaft Vibration, Misalignment	Unlikely	Gradual	Gradual	Gradual	Sudden	Unlikely
Dirt or other Contamination	Unlikely	Gradual	Gradual	Gradual	Sudden	Unlikely
Gas Entrainment	Unlikely	Sudden	Gradual	Unlikely	Unlikely	Unlikely
Assembly Error	Sudden	Gradual	Gradual	Gradual	Sudden	Sudden
Part Defect	Sudden	Unlikely	Unlikely	Unlikely	Sudden	Sudden
Excessive Transients	Sudden	Gradual	Gradual	Gradual	Sudden	Gradual

Table 2: Summary of Aging Data for Elastomers Used in CAN-Seals

EPDM: E-96-9, E-86-4, E-84-9x, E-86-5-90	10 years after cure date	20 years after cure date
Nitrile (NBR or Buna N): N-94-12, N-86-3	6 years after cure date	12 years after cure date

Service Temperature*	Rated Service Life for N-86-3 Nitrile U-Cups, Based on Hardening, & up to: 1 Mrad	20 Mrad	Rated Service Life for N-94-12 Nitrile O-Rings, Based on Compression Set, & up to 20 Mrad	Rated Service Life for All EPDM Materials Used in CAN-Seals, & up to 20 Mrad
45°C	9 years	6 years	> 9 years	> 9 years
55°C	4½ years	3 years	> 9 years	> 9 years
65°C	2¼ years	1½ years	> 9 years	> 9 years
75°C	400 days	270 days	9 years	> 9 years
85°C	200 days	135 days	4½ years	9 years
95°C	100 days	67 days	2¼ years	4½ years
125°C	12 days	8 days	100 days	200 days
135°C	6 days	4 days	50 days	100 days

* Exposure to the listed temperature for the time quoted causes the material to degrade by aging such that it becomes no longer serviceable through hardening or compression set. All rated service times are for constant servic at or below the listed temperature. However, times at different temperatures can be prorated. For example, if a nitrile U-cup sees 2¼ years service in the 45-55°C range, then the temperature drops below 45°C, its remaining service life (at < 45°C) is 4½ years, giving 6¾ years total.

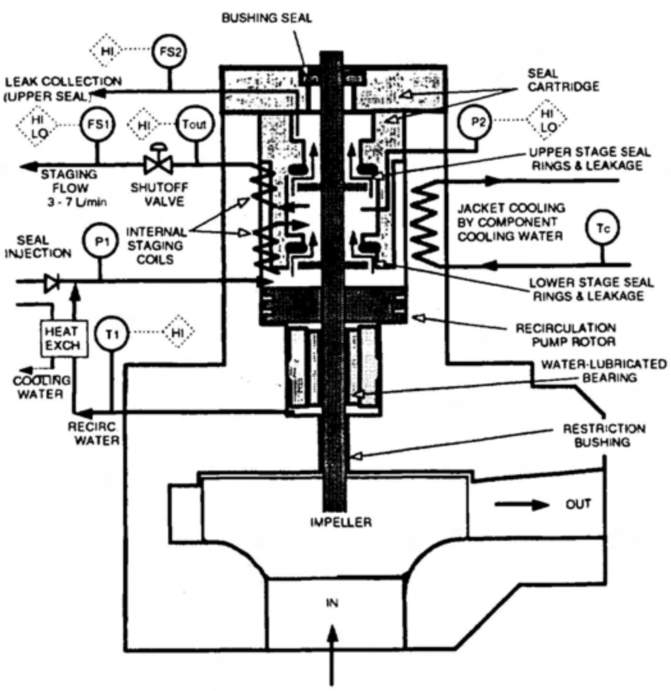
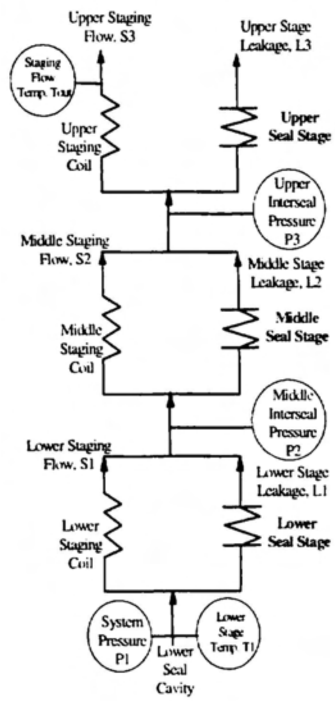


Figure 1: Typical Reactor Coolant Pump, with Two-Stage Seal



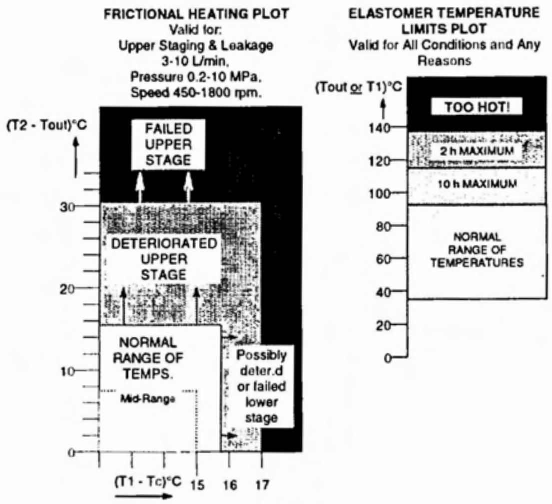


Figure 3: Temperature Criteria for Deterioration and Failure of Two-Stage CAN8C Seal

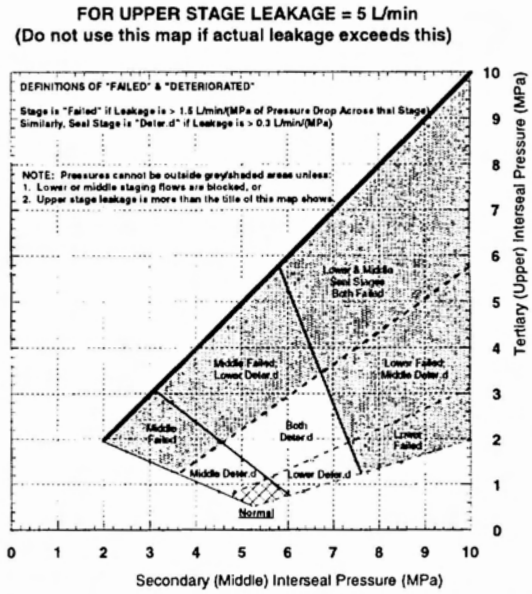


Figure 5a: Upper stage is "Failed" for Any Upper Interseal Pressures Below 3.3 MPa

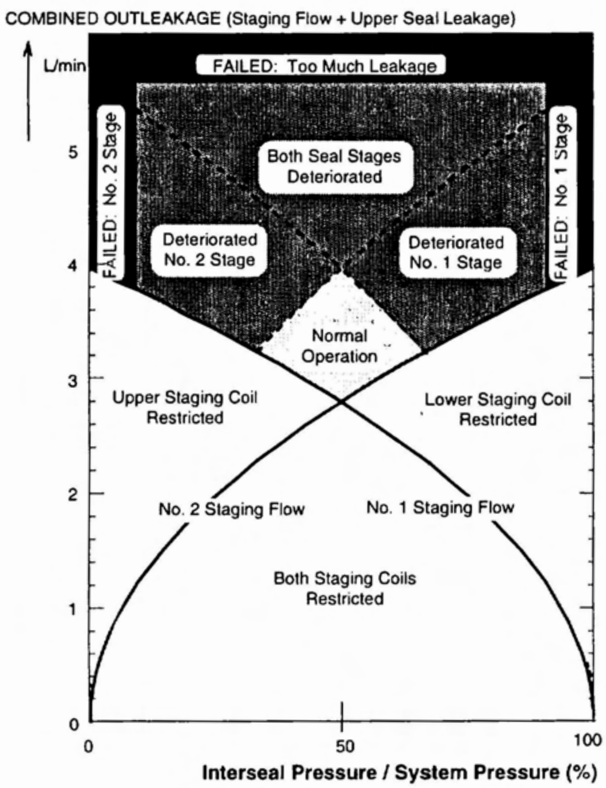


Figure 4: Seal Condition Map Showing "Deterioration" and "Failure" Boundaries for Two-Stage CAN2A Seal Cartridge

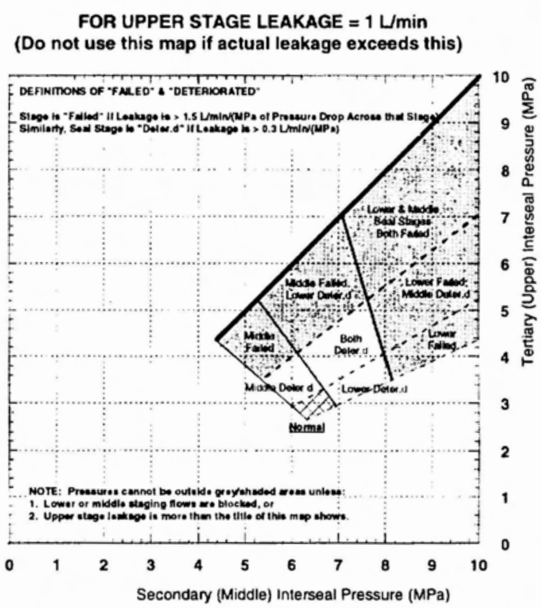


Figure 5b: Upper Stage is Borderline Between "Normal" and "Deteriorated."

PHT PUMP SEAL CONDITION MAP--
FOR UPPER STAGE LEAKAGE = 0
(Use this map if actual leakage is drops
and not as much as a steady trickle)

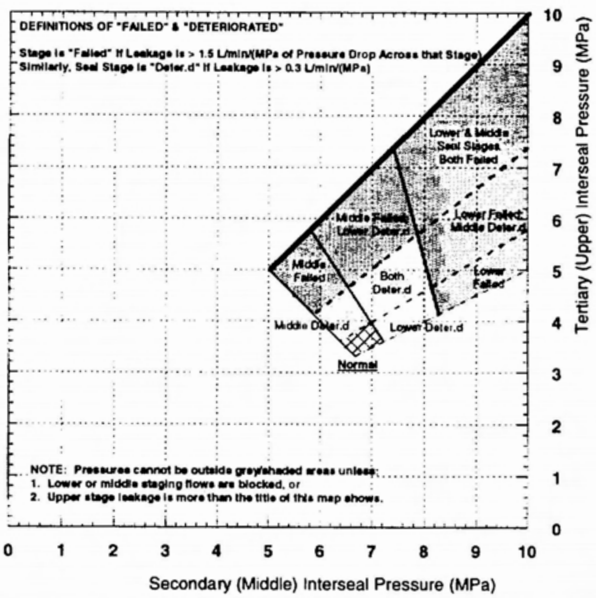


Figure 5c: Condition of Lower & Middle Stages Based on Interseal Pressures. Upper Stage Leakage "Normal" (not more than drops/min.)

	DATE / PUMP	'86	'87	'88	'89	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00
PLANT "A"	1			• →	→	→	→	→ @	→	→	→	→	→	→	→ αγ	→
17 Seal	2	• →	→	• →	→	→	→	→	→	→	⊗ →	→	λ →	→	→	→
Cartridges	3	• →	→	→	→	→	→	→	+ →	→	→	→	→	→	→	η →
Installed	4			• →	→	→	& →	→	→	→	→	→	→	→	→ β	ε →
	5			• →	→	→	→	→	→	→	→	→	◆ →	→	→	→
PLANT "B"	1					• →	→	→	→	→	→	→	→	→	→	κ →
11 Seal	2						• →	→	→	→ #	→	→	→	→ ∂	→	→
Cartridges	3						• →	→	→	→	→	→	→	→ ♣	→	→
Installed	4							• →	x →	→	→	→	→	→	→	→
	5						• →	→	→	→ ^	→	→	→	→	→	→
PLANT "C"	1										• →	→	→	→	→	→
2 Seal Instd	2										• →	→	→	→	→	→

- • First installation in each pump
- • Seal changed for preventative maintenance. Wear: 17% (#1); 5% (#2) in ~13,000 h.
- x Seal changed because accidental plant de-pressurization caused U-cup to displace. Wear: 8% (#1); 8% (#2) in ~3,000 h.
- + Seal changed to maintain pump. (Cooler repair.) Wear: 18% (#1); 29% (#2) in ~40,000 h.
- # Seal changed to maintain pump. (Cooler repair.) Wear: 20% (#1); 8% (#2) in ~27,000 h.
- ⊗ Seal changed to maintain pump. (Cooler repair.) Wear: 26% (#1); 21% (#2) in ~40,000 h.
- ^ Seal changed to maintain pump. (Coupling loose.) Wear: 14% (#1); 21% (#2) in ~30,000 h.
- @ Unknown reason for change; unrecorded wear.
- & Unknown reason for change; almost zero wear reported in ~10,000 h.
- λ Seal changed for pump maintenance. Wear: 9% (#1); 14% (#2) in ~20,000 h.
- ◆ Seal changed for preventative maintenance. Wear: 21% (#1); 14% (#2) in ~65,000 h.
- ∂ Seal changed because of slightly high interseal pressure (sleeve grooved). Wear: 26% (#1); 15% (#2) in ~35,000 h.
- ♣ Seal changed because of slightly low interseal pressure (sleeve grooved). Wear: 15% (#1); 21% (#2) in ~67,000 h.
- α Seal changed because blocked cooling hardened upper U-cup & caused de-staging. Wear: ? in ~56,000 h.
- β Seal changed for preventative maintenance. Wear said to be less than 46% in 65,000 h.
- γ Seal changed because it was set ~1/8 in. too high and de-staged. Wear: zero—barely run.
- ε Seal changed because of de-staging—dirt caused erosion. Wear said to be very little in the ~2000 h run.
- η Seal changed because of slight de-staging—dirt caused erosion. Wear: ~15% in ~53,000 h.
- κ Seal changed because of de-staging to ~30% (sleeve grooved). Wear: 17% (#1); 20 (#2) in ~85,000 h.

Figure 6: All CAN2A Seal Replacements, Reasons and Wear Data.

AECL EACL
CAN8

INFORMATION / INSPECTION SHEET NO.: IS-CAN8C-
July 2000

PART NAME: ______
PART No.: ______ Serial No.: ______
AECL DRAWING No.: ______ Rev. No.: ______ Detail No.: ______
MATERIAL: Type: ______
Compound No.: ______
Spec. No.: ______
Batch No.: ______ QA Cat.: ______
PO No.: ______ IRR No.: ______
MOULDING:
Cure Date: ______ QA Cat.: ______
SHELF LIFE: Install Before: Normal Storage (<24°C) ______ Refrigerated Storage (<4°C) ______
IN-SERVICE AGING: Good for at least 9 years in normal service at up to 75°C including 20 Mrad radiation exposure. Each 10°C increase doubles the rate of aging. Longer service at lower temperature is feasible; consult AECL for details.
QUALIFICATION TESTING: AECL Technical Procedure PR-FSTU-2

Store in the original black plastic bag, in an atmosphere free from contaminants (ozone, oil vapours, etc.), at temperatures under 24°C (75°F). For double the shelf life use refrigerated storage under 4°C (40°F).

VISUAL INSPECTION	Elastomers shall be stretched to 125% of the free circumferential length to discern any surface blemishes such as pits or cracks and note any quality defects per PR-FSTU-18.

BLANK SAMPLE SHEET
FOR ELASTOMER PART

Examined by:	Date:	Accepted by:	Date:

Part Status: ☐ Accept ☐ Reject NCR No. ______
QA Release Signature ______

Figure 7: Typical Information Sheet for CAN-Seal Elastomer Part