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White Paper on the Response of the N-Seal Reactor Coolant Pump (RCP) Seal Package to Extended Loss of All Power (ELAP)

Purpose

The purpose of this paper is to describe the design and operational features of the Flowserve N-Seal reactor coolant pump (RCP) seal package with respect to performance of the seal package after loss of normal seal cooling in a pressurized water reactor (PWR). The discussion of the ability of the N-Seal package to maintain an effective reactor coolant system (RCS) pressure boundary for an extended period of time without seal cooling is intended to clarify how the N-seal package can support a PWR that is responding to an extended loss of all AC power (ELAP).

Description of the Basic N-Seal Package

The N-Seal is a mechanical face seal package and was developed in the mid-1980's, to resolve operational and regulatory concerns with original reactor coolant pump (RCP) seals developed in the 1960's. The N-seal was designed and tested to be able to cope with a static 8 hour loss of seal cooling (LOSC) event, such as station black out (SBO), with minimal leakage. The test results and design information developed for the N-seal were provided for use in the PRA evaluations of RCP seals documented in WCAP-16175-P-A, *Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants,* Revision 0. Applicable references and test results that were provided for the WCAP-16175 evaluations are discussed in this paper as to how these tests provide insight to the response of the N-Seal design under ELAP. The N-Seal was developed and installed in Babcock and Wilcox (B&W) and Combustion Engineering (CE) nuclear plants that had Byron Jackson RCPs. Recently, the N-seal was installed in Westinghouse (**W**) pumps in **W** and B&W plants

In addition to the redundant mechanical seals of the N-seal package, a diverse and redundant seal is provided on the most recent installations of N-seal packages. This diverse seal, called the Abeyance Seal, will limit leakage from the N-seal package if excessive flow from the mechanical face seals occurs. The Abeyance seal would be demanded only after failure of all mechanical seals.

The Flowserve N-Seal is a hydrodynamic end face mechanical seal that is designed and tested for use in RCPs. The seal package is supplied in a multi-seal cartridge. Depending on the Nuclear Steam Supply System (NSSS) design, the cartridge contains either three or four identical seal stages in series. The three stage seal packages are used for **W** and B&W plants. The four stage seal packages are used for CE plants. The differences due to number of stages will be discussed later in this paper. Multiple sizes of seal, along with minor variants in face design go into the packages which are customized to fit each pump application, but the critical characteristics for resistance to loss of seal cooling (the sizes of elastomer sealed clearances, how those clearances are influenced by pressure and temperature, and the elastomer materials used to seal them) remain constant across the product family.

Although each seal stage is capable of withstanding full reactor pressure, an orifice allows flow around each of the first three stages so that during normal operation, the differential pressure across each stage is one-third of reactor coolant system (RCS) pressure. The flow through these orifices (termed pressure breakdown devices or PBDs) is referred to as controlled bleed off (CBO), or seal staging flow. In addition to equalizing the pressure across the seal stages, a second purpose of CBO flow is to remove frictional heat from the rotating seal parts.

Normal CBO flow ranges from 1 to 2.5 gpm, depending on pump model, and is much larger than the very small leakage (<0.1 gpm) across the faces of each seal stage. CBO from the third stage orifice normally is routed back to the volume control tank (VCT) for the three-stage seal packages used on **W** and B&W plants (see Figure 1). For four-stage seal packages used on CE plants, the fourth stage seal, called the vapor stage, operates at a very low pressure to combine the seal leakage from the third stage faces with the CBO flow from the third stage orifice and direct the flow to the VCT (see Figure 2).

For the three-stage packages, leakage across the third stage seal face always flows directly into the containment, typically to the reactor coolant drain tank (RCDT) or floor drains. For the four stage package, leakage across the vapor stage is directed to the containment sump.

For both the three-stage and four-stage packages, if flow to the VCT is interrupted, then generally the CBO flow will be directed to the containment via a relief valve. Flow through the relief valve instead of to the VCT will have minimal effect on seal operation. However, if flow is isolated locally at the RCP then the last stage would experience the entire pressure drop from the RCS, and leakage across the last stage as always flows into the containment.

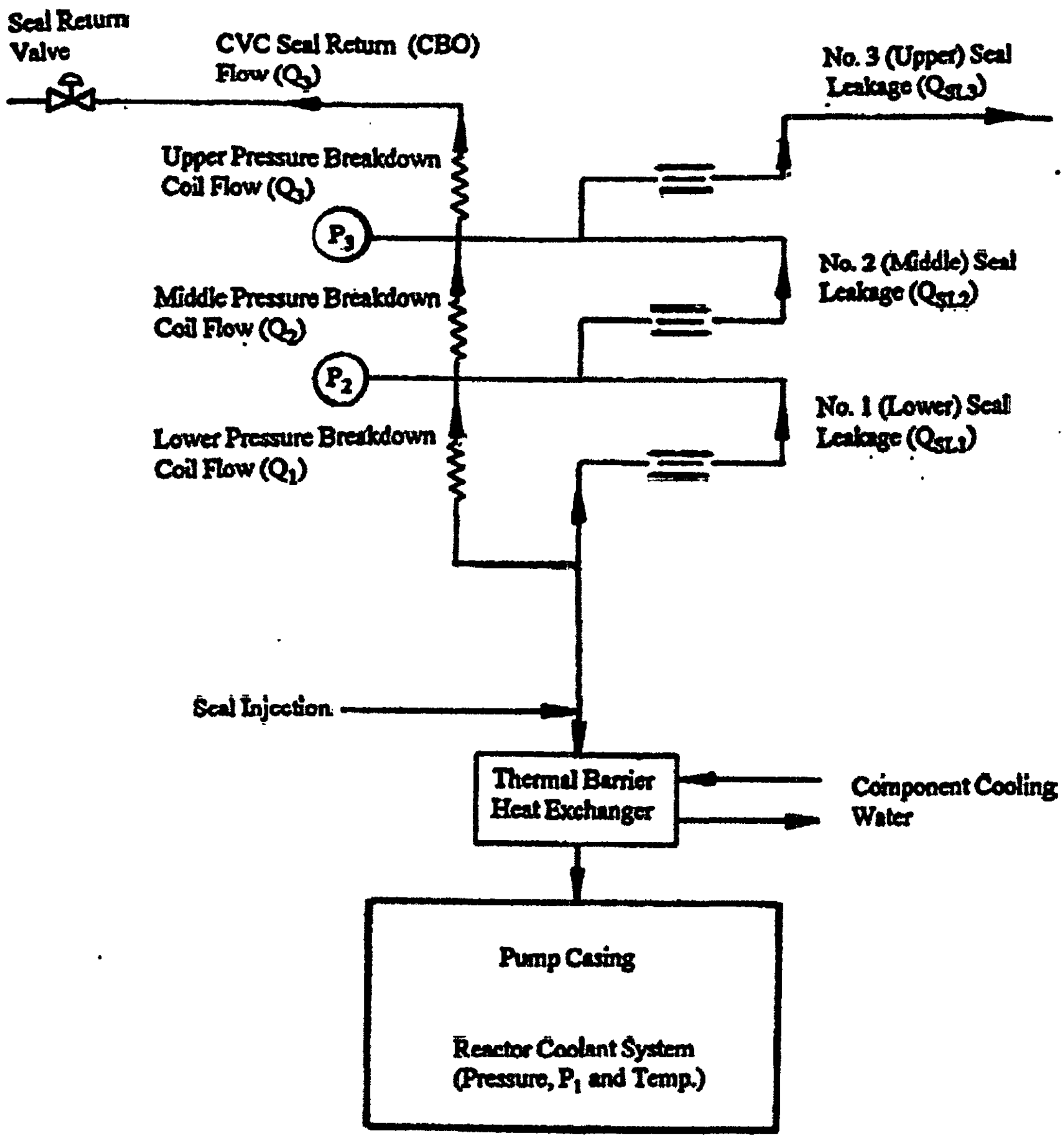

Figure 1 – Three Stage Seal and Pump Flow Schematic

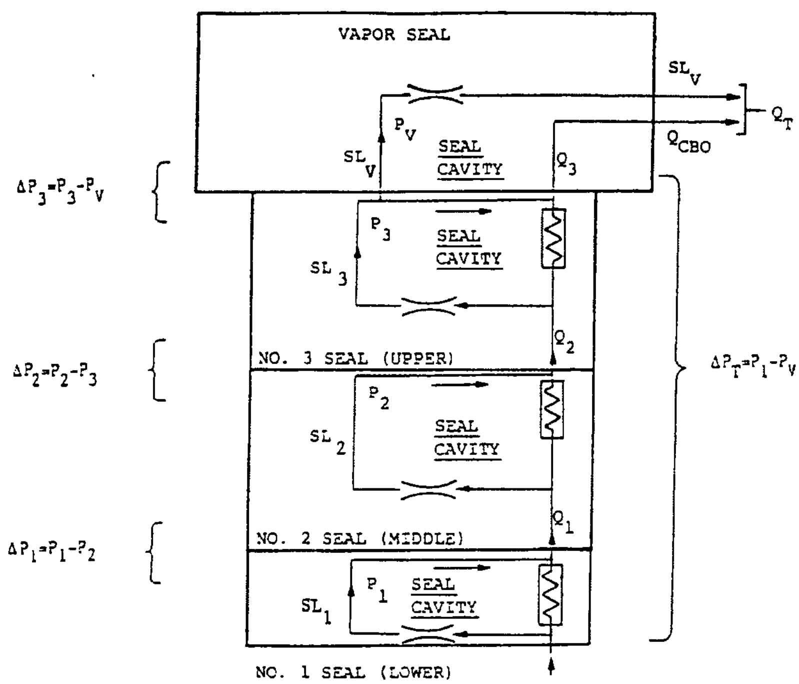

Figure 2 – Four Stage Seal Flow Schematic

The New Abeyance Seal Option

The Abeyance seal is a diverse, passive protective feature which can be included in any N-Seal cartridge above the top N-Seal stage. The Abeyance seal is being provided as a standard part of new N-seal cartridges being retrofit in W RCPs and can also be retrofit into existing N-Seals. During normal operation, there is a relatively large running clearance between the Abeyance seal and the shaft sleeve so there is no effect from normal seal leakage on the Abeyance seal. However, if the Abeyance seal is exposed to high velocity leakage, then the Abeyance seal actuates by deflection to close down the [ ][a,c] radial gap between the seal and the shaft sleeve. Closing this gap will stop leakage from the top seal to containment. High velocity leakage at the Abeyance seal can occur only after major failure of all the mechanical seal stages. For ELAP scenarios, failure of all mechanical seal stages is expected only after an extended loss of all normal seal cooling (e.g. days at ~550 °F). Under these conditions, the increased temperatures would result in the leakage being steam, which results in increased flow velocity through the failed seals due to the high specific volume of the mass being released.

After actuation of the Abeyance seal, flow out of the RCP is limited to the CBO flow. For the three-stage design, this flow is limited by the third stage seal PBD. For the four stage design on the CE plants, this flow is limited by the excess flow check valves as long as there is a functioning vapor seal or Abeyance seal above that. The Abeyance seal does not rely on elastomers because the Abeyance seal is designed to maintain a leak-tight seal for an extended time at high temperatures. In general, elastomers (even the high-temperature Ethylene Propylene compounds tested and used in the N-Seal) are not capable of remaining intact for extended times at temperatures approaching full RCS conditions (e.g. days at ~550 °F). The Abeyance seal uses a metallic sealing ring as the main sealing device. This is supplemented with an actuation ring made from poly-ether ether ketone (PEEK), a high performance engineering thermoplastic material designed specifically for high temperature applications. PEEK has a melting point of 649 °F and a glass transition temperature of 289 °F. However, since PEEK has a semi-crystalline structure, some degree of the mechanical properties is retained even close to the melting point. These properties give PEEK the ability to maintain effective sealing function at far higher temperatures than any elastomer. These properties also are maintained for much longer periods than elastomers at normal RCP seal operating temperatures during normal plant operation without decay while the Abeyance seal is in standby. Furthermore, PEEK will maintain sealing properties at full RCS conditions for an extended period of time after the Abeyance seal has been demanded. As described above, the Abeyance seal has no mechanical moving parts, and actuation involves only a small displacement of the actuation and metal sealing rings. Since there are no other mechanically moving parts in the Abeyance seal, and since PEEK has high resistance to both thermal and radiation exposure, there are no known aging mechanisms which could impede the function within the expected maintenance periods of less than 20 years.

The Abeyance seal functions as follows: the actuation ring provides initial sealing, and develops enough pressure loading [ ][a,b,c] to plastically collapse the metal sealing ring onto the shaft sleeve. After collapse of the metal sealing ring, the actuation ring ensures that the Abeyance seal is leak tight. The collapse of the metal sealing ring eliminates any finite gap and provides support across the entire actuation ring, enabling the device to withstand high pressures and temperatures for long periods. The Abeyance seal has been tested repeatedly across a range of severe conditions, including shaft offset, adherent crud coatings, up to 2500 psi and 580 °F, for durations up to 450 hours. Throughout these tests, the Abeyance seal has demonstrated the ability to actuate reliably at both low and high temperatures, and remain leak-tight as long as pressure remains behind the seal. Since the metal sealing ring is plastically collapsed at actuation, it remains as a sealing element regardless of the condition of the PEEK actuation ring. Even if near complete depressurization occurs and the actuation ring elastically returns to its original, non-contacting position (or if temperatures in excess of the tested range of 580 °F resulted in damage or deformation of the actuation ring), the metal sealing ring remains plastically collapsed against the shaft sleeve. This condition has been demonstrated by test to limit leakage to [ ][a,b,c].

Pump Seal Flow Rates During ELAP Scenarios

For all PWRs, the effect of ELAP on the RCP seals is a prolonged LOSC event. The loss of AC power will cause the RCP to stop. The ELAP also causes loss of cooling to the thermal barrier heat exchanger and loss of seal injection (if so equipped) from the charging system. The loss of seal injection will allow flow from the RCS to enter the seal package. Because thermal barrier cooling also is lost, temperature in the seal package will increase as the cool water initially in the seal package is replaced with hot water from the RCS. The rate of temperature increase will vary based on the plant, the seal, and the system configuration.

In B&W plants, the third stage PBD orifice is directly connected to the CBO line. Therefore, CBO flow is limited to the flow that can occur through the PBD. Normally, the differential pressure across each of the first three mechanical seals is one-third of RCS pressure. Since flow is proportional to the square root of pressure, the maximum liquid flow through the PBD to the CBO line is $\sqrt{3}$, or ~1.7 times the normal CBO flow of 1.5 gpm used in these plants, if the full RCS pressure was on the third stage. Testing has shown that estimated flow rate to be within 10% of the actual flow under two phase conditions.

In B&W plants (as well as some CE plants), an isolation valve in the CBO flow return path can be closed and kept closed during LOSC events without merely redirecting flow to containment via a relief valve. Therefore, CBO in those plants can be stopped after a LOSC event and leakage from the RCP seal limited to the leakage across the top seal stage. An Abeyance seal can be retrofit to these N-Seal packages to provide backup to limit this leak path as well.

In all CE plants with N-seals, the vapor seal stage combines and redirects the third seal leakage and third stage CBO orifice flow to the CBO return flow path. As such, CBO flow is limited only by resistance through the potentially-failed first three seal stages and the seal flow return line. To address this, CE plants additionally have an excess flow check valve in this line which will close when flow exceeds a specified value, typically 15 gpm. Actuation of this excess flow check valve will redirect the full RCS pressure to the vapor seal, and/or abeyance seal (if so equipped).

Isolation of the CBO flow path reduces the direct inventory loss from the RCS. Isolation also results in a thermal gradient within the stagnant areas of the seal cartridge. [

][b,c] At the same time, isolation of CBO causes full RCS pressure to be applied to the top stage seal, tripling the pressure related stresses in all components, particularly the elastomers. Therefore, while isolation results in lower inventory loss and lower temperatures at the seals, the subsequent pressure stresses are more severe on the seal components. The analysis in WCAP-16175 considered cases where isolation occurred as well as where isolation failed and concluded that the additional stresses were not significant to the overall seal performance.

The CBO flow in **W** pumps is routed through the line previously used for number 1 seal leakoff. There is an isolation valve in this line local to the RCPs but the valve typically requires instrument air to close and remain closed. The piping and associated containment isolation valves on the CBO line downstream of the local isolation are not rated to full reactor pressure. Therefore, there is a relief valve between the isolation valve local to each RCP and the containment isolation valve. This relief valve opens to redirect CBO into containment when flow to the VCT is blocked by isolation of that line.

Containment isolation valves for instrument air may receive a signal to close during events that result in loss of RCP seal cooling. In addition, the ELAP causes a loss of power to the instrument air compressors so instrument air is, by definition of the event, unavailable. Loss of instrument air will result the opening of the local CBO isolation valve on **W** pumps. Therefore, this evaluation assumes that isolation of CBO is not possible on **W** pumps, and, that the minimum baseline flow from each RCP, with no seal failures, is the nominal 2.5 gpm per pump normal CBO flow. However, if CBO, including flow from the CBO line relief valve, can be isolated (typically requiring some plant modification such as valve changes), then lower, potentially negligible, total flows from the RCPs will occur.

In addition to the flow which may be passing through the third stage PBD, there will be leakage past the third stage seal faces. As mentioned above, this flows into containment in B&W and **W** pumps, and mixes with the CBO flowing into containment via the relief valve for CE plants if local isolation is not performed. Based on the Flowserve test data used in the WCAP-16175 analyses, the expected leak rate past the third stage seal is < 0.04 gpm for LOSC events lasting less than 8 hours with temperatures at the first stage seal less than 555 °F and a [ ][b,c] (discussed above). Testing also included shorter duration exposure of approximately [ ][b,c]. Post-test examination of the seals revealed no charring or other gross chemical deterioration characteristics that would indicate any change in degradation mode relative to these higher temperatures. Therefore, no change in the degradation rate is expected for the slight increase in temperatures evaluated in the tests. Nevertheless, actions that preclude cold leg temperatures from exceeding 560 °F would keep conditions at the RCP seals within tested limits and obviate any need to extrapolate the response of elastomers to higher temperatures than were evaluated in the testing. The elastomer components in the mechanical seal stages should not experience any significant change in failure modes for short periods of time, e.g., 24-hours or less. However, if seal cooling is lost for longer than 24 hours and RCS temperature remains high, failure of elastomer components in the mechanical seal stages becomes progressively more likely.

On loss of all seal cooling, injection from the charging system will stop. Then flow of reactor coolant from the RCS to the seal leak-off line will begin. Initially, the flow will be the cool water that was injected to the seals and that is surrounding the thermal barrier heat exchanger. An extended loss of seal cooling event will allow hot water from the RCS cold leg to flow into the seals and RCP seal temperature will approach cold leg temperature. Based on WCAP-16141, *RCP Seal Leakage PRA Model Implementation Guidelines for Westinghouse PWRs*, the volume of cold water in the RCP above the cold leg will nominally be purged in 13 minutes. Initial leak rates from the **W** # 1 seal are assumed to be between 1.5 and 5 gpm. For the N-seal package, however, flow from the RCS through the RCP seals is nominally 2.5 gpm. The time needed to purge cold water from the seals is directly related to the flow rate (e.g. using a CBO flow rate of 2.5 gpm for the N-seals instead of the mean 3.25 gpm flow rate given in WCAP-16141, the cold water around the N-seal package would not be purged for ~17 minutes using the same simplistic approach). [

]^{a,c}. Additionally, the N-seal has been demonstrated by testing to have no negative effects from rapid cooling (up to 1300 °F/hr). Since the N-seals are not subject to adverse effects from rapid cooling, restoration of seal injection from normal or alternate sources can occur at any time without risk of seal failure (although it could cause warping of the pump shaft as discussed in **W** operating instructions). Once seal injection is reestablished, thermal degradation of elastomers would be arrested, potentially preventing failure of the primary seal stages at the possible expense of temporary loss of pump operability or later significant pump maintenance, depending if the shaft thermal bow resulted in permanent deformation.

On the other hand, if pressure and temperature are reduced from full system conditions (approximately 555 °F) to 425-350 °F or less in a shorter duration, such as two to six hours, then the elastomer degradation rate is greatly reduced. Since the specific LOSC test temperatures on these materials bound the reduced temperature condition, it is very reasonable to use the Arrhenius correlation to predict the ratio of thermal degradation with time. Using the .95eV activation energy for Ethylene Propylene elastomers, (ref. EPRI NP-1558), the calculated ratio of time at 350 °F to equivalent damage at 555 °F is more than 140, whereas the parallel ratio for 425°F is approximately 18. Further, the order of magnitude reduced system pressure which would accompany such a reduction in temperature proportionally reduces the mechanical stresses in the elastomers. It is these stresses at high temperatures that lead to the elastomer failure modes of extrusion and compression set. From all this data, it is concluded that degradation of the elastomers in the first three primary N-seal stages is not likely if pressure and temperature are reduced in the first six hours. Therefore, it is unlikely that the Abeyance seal would be challenged (in pumps equipped with one) if the RCS is cooled and depressurized in a timely manner. Individual evaluations of plant specific pressure and temperature profiles may be required for longer scenarios to determine if existing Flowserve N-seal SBO test data can be shown as encompassing those conditions when overall cumulative exposure to temperature and pressure are considered, as well as maximum temperature seen.

Figure 3 is a compilation of the test parameters that the N-Seal has withstood during this test. As discussed in the detailed Flowserve test report which was used as a reference in WCAP-16175, the test involved a combined scenario modeling loss of RCS inventory and pressure, with the concurrent downward shaft motion that challenges the seal with opening forces from friction and any binding or hangup, followed by pressure increase simulating interruption of natural circulation. Seal leakage held at 0.04 gpm after CBO was isolated in the first hour, despite the shaft motions. After more than 8 hours since the initial heatup, an elastomer failure in the third stage increased the leakage to 1.65 gpm and reinitiated seal pressure staging. The test was terminated shortly thereafter for safety reasons due to an external tester leak, having reached all the desired goals, but the 1.65 gpm leakage value held during the subsequent ~2 hour cooldown and depressurization, showing that the limiting factor was choked two-phase flow through the formerly elastomer sealed clearance flow path. A typical proposed ELAP scenario is included for reference. A simple nominal linear heatup time has been added as discussed above, but conservatively no attempt has been included to consider the steady state thermal gradient from the plant supplied ELAP values for the cold leg conditions to the actual temperatures in the seal area.

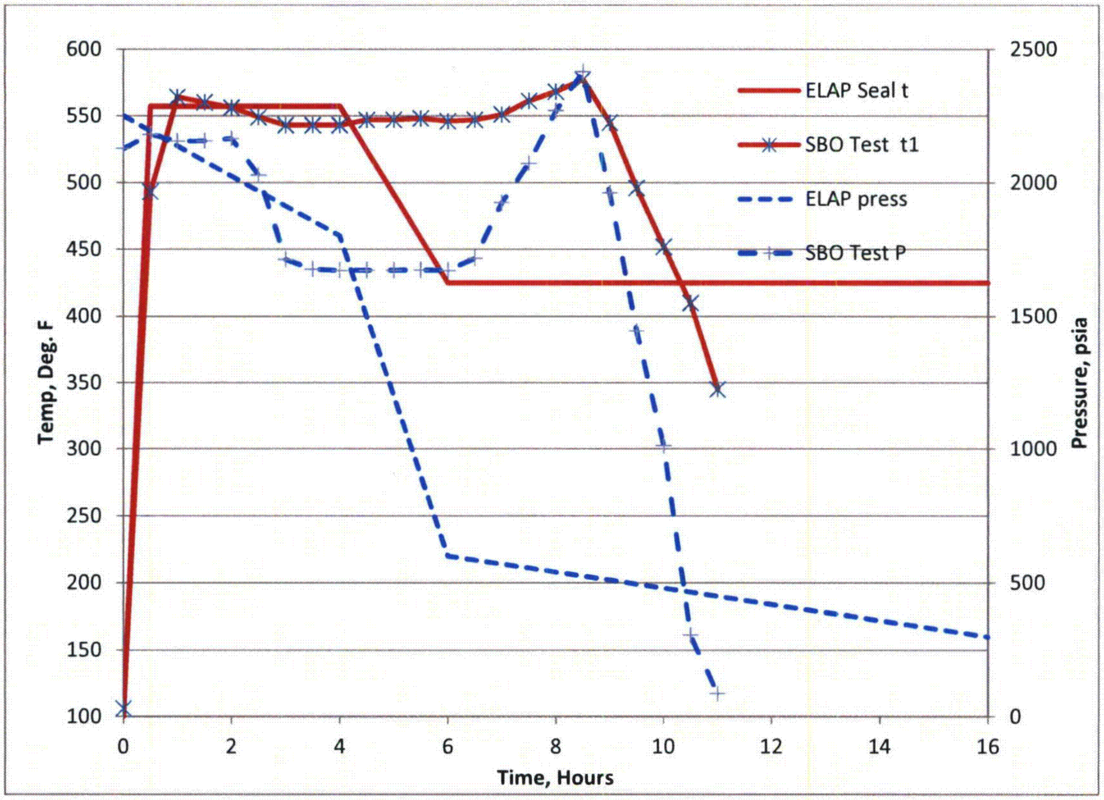

Figure 3 – Comparison of Flowserve N-Seal SBO Test Data to Typical Proposed ELAP

For scenarios where RCS pressure and temperature cannot be reduced, eventually seal stage failures due to elastomer degradation will become more likely. Under greatly extended periods without reduction in pressure and temperature (e.g. days), the elastomer failure would approach certainty. Various failure modes of different combinations of the three redundant N-seal stages can increase the total outflow from the RCP. In pumps without Abeyance seals, this leakage would likely have some restriction by the very close **elastomer sealed** clearances [ ]a,c and tortuous leak paths that elastomer failures would allow, but are only firmly bounded by the larger fixed diametric **running** clearances between the pump rotating and stationary parts (such as those referenced in WCAP-16175). For this reason the Abeyance seal was developed to prevent the potential very large leakage past the top seal stage in the event of gross degradation of all the primary N-Seal stages. Still, the Flowserve test data discussed above has shown that single elastomer failures, even if repeated on all three seal stages, will not result in leakage [ ]a,b,c. Each of the seal stages must experience multiple elastomer or other, more significant (and less plausible) failures to result in higher leakages.

To actuate the Abeyance seal on pumps that are so equipped, the failures of all the mechanical face seals of the RCP seals must result in an initial total flow rate of [ ]a,b,c past the top seal stage. If flow [ ]a,b,c past the top stage, then a total outflow from the RCP of no more [ ]a,b,c will occur for a **W** RCP. This flow is based on [ ]a,b,c needed to actuate the Abeyance seal and 4.3 gpm maximum flow through the third stage PBD into the CBO line that is expected given the bounding scenario of complete failure of the first two seal stages, and a lesser, but still significant failure of the third seal stage. Lesser values would be predicted for the lower nominal 1.5 gpm CBO flow through the orifices in Byron Jackson pumps in B&W plants, if those RCPs were retrofit with Abeyance Seals. CE pumps, if retrofit with Abeyance seals, could have a bounding leakage value in extreme scenarios which would first result in degradation of the three high pressure stages, then challenging the vapor seal after the excess flow check valve is actuated. This would be based on the sum [ ]a,b,c needed to actuate the Abeyance plus the value required to close the excess flow check valve in the CBO line. However, since the vapor seal is only challenged after the actuation of the excess flow check valve, with any scenario that includes cooling and depressurization these conditions will never be reached. As no CE or B&W plant using Byron Jackson RCPs has yet committed to retrofitting with Abeyance seals, the remainder of the discussion will focus on **W** pumps.

Since [ ]a,b,c is required to generate enough force to deflect the actuation ring, certain failure modes of the N-seal package may result in flow rates that are not large enough to actuate the Abeyance seal. The main factor affecting whether or not the Abeyance seal actuates is the failure mode of the top stage seal. Specifically, failure of the elastomer components in the top stage would provide only a very small flow area for leakage, and thus could result in flow rates of less than [ ]a,b,c past the third seal stage. That flow would be insufficient to actuate the Abeyance seal. Although the specific failure mode for each of the first two stages has some small effect on the flow rate expected through the third stage elastomer failure, the difference in flow expected is slight. Regardless of the failure mode of the first two stages (e.g. even if the first two stages underwent some other failure than elastomer decay which resulted in the gross loss of sealing ability), the total flow through the elastomer failure of the third stage would be less [ ]a,b,c initially.

Although the flow rate from elastomer failures could be expected to increase over long periods of time, this paper assumes that the flow remains constant if an elastomer failure results in flow that is not high enough to actuate the Abeyance seal for pumps that are equipped with one. This assumption that the flow rate from an elastomer failure does not increase is conservative in this case in that it results in the highest mass loss from the reactor coolant system (RCS) over time. If a slight increase in flow through the failed elastomer is considered, then actuation of the Abeyance seal should occur and fluid loss through the failed RCP seals would be limited to the flow through the CBO line, 4.3 gpm per pump maximum for **W** RCPs equipped with Abeyance seals.

Therefore, this evaluation assumes for **W** pumps equipped with Abeyance seals, that any failure of the first two seal stages in combination with failure of an elastomer component in the third stage will result in flow through the failures that is just below the flow needed to actuate the Abeyance seal and that the flow will remain constant over time. That is, actuation of the Abeyance seal will not occur.

Failure of the first two seal stages accompanied by failure of the third stage due to any cause other than failure of an elastomer component should actuate the Abeyance seal. Successful actuation of the Abeyance seal will stop flow through the failed RCP seals and flow would be limited to the flow through the pump CBO line to the aforementioned maximum of 4.3 gpm. However, if the Abeyance seal fails, then increased flow along the RCP shaft is expected. The specific flow expected will depend on the specific failure mode for each of the seal components. However, total flow will be limited by the clearance available between the shaft and the seal components. In the limit, this flow will be less than 480 gpm per pump (based on the current bounding leakage values for the **W** RCP). Although certain failure mode combinations could result in initial flow significantly less than 480 gpm per pump, the flow rate could increase over time. To simplify modeling, any failure of the Abeyance seal to actuate when demanded is assumed to result in flow of 480 gpm per pump in the PRA model. For this evaluation, again, any plant scenario which includes cooldown is not likely to ever exceed the capability of the N-seal, so this value would not be applicable.

In summary, the actual flow rates expected from failures of the seal stages are listed below for a **W** RCP equipped with an N-Seal that includes an abeyance seal.

Scenario	Bounding Total Leakage (per Pump)
No stage failures	2.5
Any one stage failed	3.1
Any two stages failed	4.3
3 stages failed, abeyance actuation	4.3
3 stages failed, 3rd stage leak below abeyance actuation	[ ]a,b,c
3 stages gross failure + abeyance failure	480

Seal Failure Probability Values

Probabilistic failure models of the N-Seal with Abeyance RCP seal package have been developed for certain utilities. These models use as their basis the logic model and the data in WCAP-16175-P-A, *Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants*. That report was provided by the utilities for use in the analysis. Failure values for application of the N-seals to CE plants can be developed from WCAP-16175. The additional failure of the Abeyance seal has been addressed in the new failure model for the three-stage configuration. This information is included here for reference only.