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PRA Model for RCP Seal Failure Given Loss of Seal Cooling for APR1400 KSB HDD-254 Type F RCP Seals

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PRA Model for RCP Seal Failure Given Loss of Seal Cooling for APR1400 KSB HDD-254 Type F RCP Seals

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ACRONYMS AND TRADEMARK

Acronym	Definition
AC	Alternating Current
AAC	AC Power Source
ADV	Atmospheric Dump Valve
ANS	American Nuclear Society
APS	Arizona Public Service
ASME	American Society of Mechanical Engineers
AECL	Atomic Energy of Canada Limited
BJ	Byron Jackson (now Flowserve: formerly BW/IP)
BNL	Brookhaven National Laboratory
CBO	Controlled Bleedoff
CCF	Common Cause Factor
CCW	Component Cooling Water
CE	Combustion Engineering
CEOG	Combustion Engineering Owners Group
CVCS	Chemical & Volume Control System
DCA	Design Certification Application
ELAP	Extended Loss of AC Power
EP	Ethylene Propylene
EPDM	Ethylene Propylene Diene Monomer
EOP	Engineering Operating Procedure
GSI	Generic Safety Issue
HPI	High Pressure Injection
HSS	Hermetic Stillstand Seal
HRA	Human Reliability Analysis
IE	Initiating Event
KEPCO	Korea Electric Power Corporation
KHNP	Korea Hydro & Nuclear Power
KSB	Klein Shanzlin Becker
KWU	Kraftwerk Union
LOCA	Loss of Coolant Accident
LOCC	Loss of Component Cooling

LOCCW	Loss of Component Cooling Water
LOOP	Loss of Off-Site Power
NOP	Normal Operating Pressure
NOT	Normal Operating Temperature
LOSC	Loss of Seal Cooling
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
PBD	Pressure Breakdown Device
[	]^{a,c}
PRA	Probabilistic Risk Assessment
psia	Pounds per square inch, absolute pressure
psig	Pounds per square inch, gage pressure
PTCV	Passive Thermal Check Valve
PVNGS	Palo Verde Nuclear Generating Station
PWR	Pressurized Water Reactor
RB	Reactor Building
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RDT	Reactor Drain Tank
RPS	Reactor Protection System
SBO	Station Blackout
SER	Safety Evaluation Report
SFOON	Seal Stage Failure Event
SG	Steam Generator
SI	Safety Injection
SIT	Safety Injection Tank
SONGS	San Onofre Nuclear Generating Station
SSC	Structure, System, and Component
TR	Topical Report

EXECUTIVE SUMMARY

WCAP-16175-P-A (Reference 1), "Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants," documented failure models derived to determine the importance of reactor coolant pump (RCP) seals, of different designs, to plant risk. The report specifically presented RCP seal models for Combustion Engineering (CE) plants with Bingham and/or Flowserve RCP seals. The report did not specifically include the KSB RCP seal manufactured by Klein Shanzlin and Becker (KSB) since such seals were not in use in the United States at the time the topical report (TR) was prepared. However, the seal designs, failure mechanisms, and causes of loss of seal cooling (LOSC) considered in that report can be applied to seal designs and seal-pump combinations for other pressurized water reactors (PWRs) employing hydrodynamic RCP seal designs. In order to utilize that report for an alternate, but similar, RCP seal design, the United States (U.S.) Nuclear Regulatory Commission (NRC) Safety Evaluation Report (SER) included in that TR noted that in "applying the model to non-CE plants {i.e., non-included RCP seal/RCP combinations}[1] the utility should ensure that the model accurately reflects the operation, experience and knowledge of the specific plant with these RCP seal packages". Specific limitations and conditions of use that apply to the U.S. NRC approval of Reference 1 were listed in Section 4.0 of the SER.

The purpose of this report is to extend the application of the model for quantifying the probability of a RCP seal failure, given a LOSC, developed in Reference 1 to the KSB's HDD-254 Type F RCP hydrodynamic seal design employed in the APR1400 RCPs. This work was performed in support of the APR1400 Design Certification Application (DCA) Project.

This report includes operating experience performance data from KSB and Korea Electric Power Corporation (KEPCO) for KSB RCP seals installed at PWRs in Europe and Korea. In addition, the report updates the RCP seal failure parameters to reflect station blackout (SBO)/extended loss of AC power (ELAP) separate effects and integral testing performed at KSB on the HDD-254 Type F RCP seal. Seal leakage rates were also updated to reflect the current KSB pump and seal arrangement. Quantification results for the Type F RCP seal failure probabilities following a LOSC event are presented in Table 9.1-7 which include extension to 72 hours to address the (ELAP) time frame.

Results of the analysis indicate that the KSB HDD-254 Type F seals have conditional failure probabilities for a 24-hour duration LOSC event range from [$]^{a,c}$ depending on the status of CBO isolation. These failure rates are approximately [$]^{a,c}$ lower than those associated with the 3-stage seal package evaluated in Reference 1 (see Table 9.2-1). Thus, the Type F seal is predicted to have robust capability to accommodate LOSC events.

Seal failure probabilities for degraded operation (one stage inoperable) are also provided for use in off-design operational assessments (see Section 10). RCP operation in the presence of a degraded/failed seal stage significantly increases the LOSC conditional failure probability, suggesting that extended operation with failed seals can impact the plant risk profile.

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[1] Brackets added by author.

1 INTRODUCTION

1.1 PURPOSE

WCAP-16175-P-A (Reference 1), “Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants,” documented failure models derived to determine the importance of RCP seals, of different designs, to plant risk. The report specifically presented RCP seal models for CE plants. However, the failure mechanisms and causes of LOSC considered in that report can be applied to seal designs and seal-pump combinations for other PWRs employing hydrodynamic RCP seal designs. In order to utilize that report for alternate, but similar, RCP seal designs, the U.S. NRC SER included in Reference 1 noted that in “applying the model to non-CE plants {i.e., non-included RCP seal/RCP combinations}[2] the utility should ensure that the model accurately reflects the operation, experience and knowledge of the specific plant with these seal packages”. Specific limitations and conditions of use that apply to the U.S. NRC approval of Reference 1 were listed in Section 4.0 of the SER.

The purpose of this report is to extend the application of the model for quantifying the probability of a RCP seal failure, given a LOSC, developed in WCAP-16175-P-A to KSB HDD-254 Type F hydrodynamic seal design employed in the APR1400 RCPs. This work has been performed in support of the APR1400 DCA.

1.2 SCOPE

This report provides a Probabilistic Risk Assessment (PRA) LOSC failure model for the KSB HDD-254 Type F RCP Seal/KSB RCP combination planned to be installed on the APR1400 plants.

While the normal operational characteristics of the Type C and Type F seal are virtually identical, enhancements implemented in the Type F seal provide a significant increase in the robustness of the RCP seal package to SBO events. These features include modified manufacturing of the seal constituent parts to minimize thermal stress and control elastomer seal quality and to increase the secondary seal resistance to high temperatures during seal heatup scenarios following LOSC events. These changes have been judged by KSB to have a negligible impact on normal RCP seal operation, but have been shown to have a dramatic effect on the ability of the seal to cope with a long duration SBO. However, it is noted that the Type F seal has no operational history; therefore, this report incorporates relevant Type C seal operational experience data to estimate seal component reliability parameters for random and pre-existing failure probabilities which are considered to be representative of the Type F seal performance during normal operation.

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[2] Brackets added by Author.

1.3 BACKGROUND

While not formally considered a RCS boundary, RCP seals provide protection to the RCS from loss of RCS inventory, limiting leakage of inventory from the RCS to a small CBO. The potential for unacceptable leakage primarily arises from induced seal failures following a LOSC resulting in operation of the seal package at high temperatures, well above intended design conditions. Although individual stage failures and LOSC events have occurred in multistage hydrodynamic seals typical of those in CE-designed PWRs, no RCP seal package failures have occurred (Reference 1).[3]

On July 14, 1999, the U.S. NRC held a meeting with representatives of the three PWR owners groups to discuss their plans for resolution of Generic Safety Issue (GSI) 23, *Reactor Coolant Pump Seal Failure*.[4] At that time, the U.S. NRC noted that the generic issues program was being revised. Under the new regulatory process, "closure" of an issue means it is closed and no further action is needed. "Resolved" means that sufficient information is available to assign the issue a low priority for "closure". The U.S. NRC noted that they would be using "risk-informed" decision making in the revised generic issues program.

The U.S. NRC approach to GSI-23 was to "resolve" the issue. The U.S. NRC felt that the remaining elements of the issue were no longer generic and should be handled on a plant-specific (or owners group-specific) basis. The primary feature required to completely resolve the issue for plants operating with hydrodynamic RCP seal designs would be to use PRA techniques to ascertain the importance of RCP seal failure to individual plant risk. To this end, the U.S. NRC encouraged the utilities to develop a mechanistic seal failure model plant PRA including consideration for plant-specific operational procedures and actions taken during SBO and loss of cooling to the seals.

To close this issue, the Combustion Engineering Owners Group (CEOG) funded a program to review and evaluate applicable seal stage failure and test data with the intent of developing a mechanistic seal stage PRA model. The resulting RCP seal failure model was based on a combination of operating experience, tests on RCP seals, available analytical models, and reasonable assumptions based on expert judgment. The model was used to establish the probability of a Loss of Coolant Accident (LOCA) due to seal failure caused by a total LOSC. At the time that the evaluations were performed one CE utility, Arizona Public Service (APS), included three System 80^{TM} units (PVNGS Units 1, 2 and 3) fitted with KSB RCPs. These pumps were initially installed with KSB Type A RCP seals, but the seals were replaced with Sulzer Balanced Stator 3--stage seals in 1996. Therefore, at the time of the analysis, none of the APS units was operating with a KSB RCP seal; consequently, KSB seals were not reflected in the basic event parameter tables within the scope of the baseline RCP seal PRA model.

The initial analytical task developing CE RCP seal models was completed in July of 2000. PRA models were established for three CEOG member seal designs including a 3-stage Sulzer 950B seal package with

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[3] Based on information provided to Westinghouse, no LOSC events have occurred on KSB RCP seals in Korea or Germany. In addition, operational experience with these seals have been excellent (see Section 5).

[4] Closure of GSI 23 is documented in memorandum from A. C. Thadani to W. D. Travers, "Closeout of Generic Safety Issue 23, Reactor Coolant Pump Seal Failure," dated November 8, 1999 (Accession Number ML993370509).

non-uniform pressure breakdown, which is similar to the KSB RCP seal design. PRA models were developed to encompass a wide range of operational plant states and CBO isolation procedures. Plant-specific leak rates for all seal/pump combinations included within the CE fleet were also established. The approved version of this report was issued in January 2004 as WCAP-16175-P-A (Reference 1).

As the KSB RCP seal is a hydrodynamic seal, the framework of this model is generally applicable to the KSB RCP seal design. Differences in the present model arise from model updates that capture the impact of KSB RCP seal-specific elastomer data and operational experience.

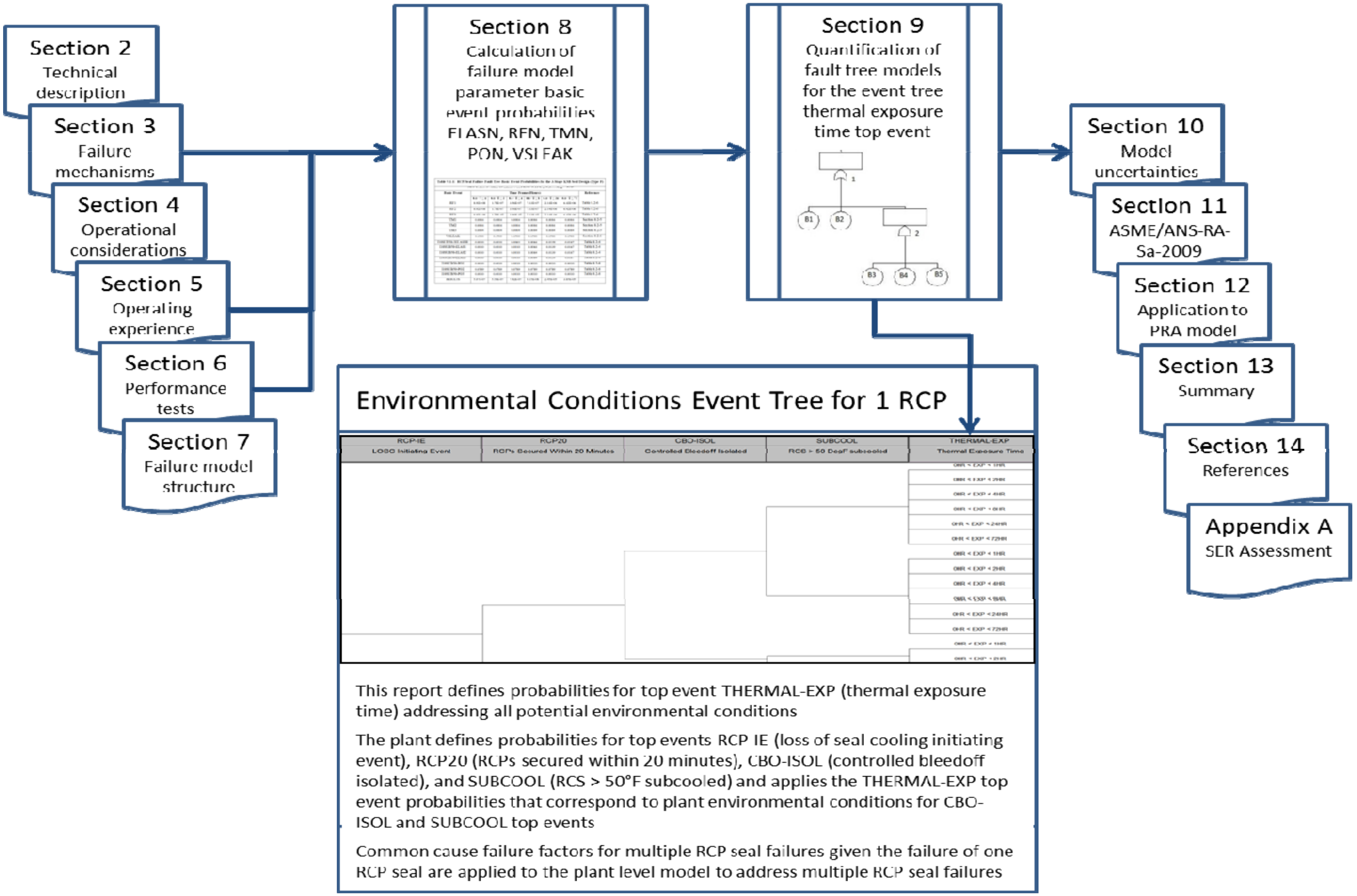
1.4 PRESENT MODEL

This report utilizes the information presented in WCAP-16175-P-A, referred to as the TR, and extends the applicability of the RCP seal failure probability model structure to the KSB HDD-254 Type F RCP seals. This report is developed consistent with the intent of the U.S. NRC SER of the TR and specifically addresses relevant high level and supporting requirements of ASME/ANS RA-Sa-2009 (Reference 2). A comparison of the present model to the relevant requirements in Reference 2 is presented in Section 11. An assessment of this model demonstrating compliance with the SER conditions and limitations is summarized in Appendix A.

The report is arranged as follows:

- Section 2 documents the design features and limits for seal operation under normal, abnormal, and shutdown conditions.
- Section 3 is a review of the seal stage failure mechanisms
- Section 4 summarizes operational considerations affecting seal performance
- Section 5 describes KSB RCP seal operating experience
- Section 6 summarizes relevant experimental data important to understanding post-accident performance of the RCP seal
- Section 7 describes the KSB RCP seal failure model
- Section 8 includes the calculation of APR1400 specific KSB Type F RCP seal failure parameters
- Section 9 provides the quantification of the Event Tree thermal exposure time top event and fault tree models for the KSB Type F RCP seal PRA model
- Section 10 addresses RCP seal model uncertainty
- Section 11 identifies and evaluates high level and supporting requirements of Reference 2 relevant to the development of this model
- Section 12 provides high level implementation guidance
- Section 13 summarizes conclusions based on the quantification results
- Section 14 includes a list of references
- Appendix A provides an assessment of the model against SER conditions and limitations

Figure 1-1 depicts the inter-relationships among the above sections. The failure model integrates seal design features, relevant KSB seal operational experience, results of KSB related experimental test programs, and expected seal environmental conditions following a LOSC initiating event to establish a post-accident event tree. This information is then used to construct and create failure parameter distributions (random variables) to populate a probabilistic dynamic seal fault tree. A probabilistic tool is then used to propagate the seal parameters to obtain seal failure probabilities given specified accident sequences resulting from a LOSC. These seal failure probabilities are provided as a function of timing of CBO isolation, RCS subcooling, and the duration of thermal exposure during the LOSC event. Mean seal failure probabilities for the KSB Type F RCP seal can be found in Table 9.1-7.



This report defines probabilities for top event THERMAL-EXP (thermal exposure time) addressing all potential environmental conditions

The plant defines probabilities for top events RCP IE (loss of seal cooling initiating event), RCP20 (RCPs secured within 20 minutes), CBO-ISOL (controlled bleedoff isolated), and SUBCOOL (RCS > 50°F subcooled) and applies the THERMAL-EXP top event probabilities that correspond to plant environmental conditions for CBO-ISOL and SUBCOOL top events

Common cause failure factors for multiple RCP seal failures given the failure of one RCP seal are applied to the plant level model to address multiple RCP seal failures

Figure 1-1: Seal Failure Model Flowchart

2 TECHNICAL DESCRIPTION OF THE APR1400 KSB HDD-254 TYPE F RCP SEAL

2.1 KSB RCP SEAL DESIGN

KSB seals for RCPs were initially developed in the 1970s. The initial KSB RCP seal was HDD-254 Type A. The KSB RCP seals consisted of a 3-stage hydrodynamic design with each stage capable of retaining full system pressure. The Type A seals were initially installed in the CE PVNGS units and several reactors in Germany. The seal stage faces were designed with one tungsten face and one antimony impregnated carbon face. Tungsten-antimony erosion and carbon wear among other issues led to the development of the Type C seal. Operational issues with the Type A seal in the United States resulted in PVNGS units adopting an alternate seal supplier in the 1990s. The Type C seal was developed in the 1980s and included Silicon carbide-carbon composite (SiC) for both the rotating and stationary seal faces. This combination was operationally superior to the Type A seal. HDD-254 Type C seals have been installed in over 100 RCPs in Europe and Korea. Type C seal designs were integrated into the Korean fleet in Shin-Wolsong Units 1 and 2 and Shin Kori Units 1 and 2. Experience in Germany indicates that Type C seals demonstrate excellent operation. KSB has further noted that the seal reliability is very high and, to their knowledge, Type C RCP seals have not resulted in a reactor trip or necessitated an exigent shutdown (Reference 6).

While the Type C seal design has been successful during normal operation, the Type C seal's ability to cope with total loss of cooling events is a potential concern. KSB notes that the seal design and elastomer materials [i.e., commercial quality ethylene propylene (EP)] used in the Type C have questionable long-term performance at temperatures above [.]^{a,c} Detailed analyses of the Type C seals following total LOSC events typical of SBO scenarios suggest seals will degrade over time, increasing the potential for seal leakage.

The need for improved SBO performance has led to selected improvements in the design of the Type C seal. The revised Type F seal is currently planned for use in future KSB RCPs. The Type F seal has been designed with SBO considerations in mind. These enhancements include redesign of seal components to increase margin for thermal expansion and improved temperature resistance of Ethylene Propylene Diene Monomer (EPDM) elastomers with a [[5]]^{a,c}. [ ]^{a,c} Furthermore, Type F seal tests indicated that seal elastomers (O-rings) can successfully operate at [ ]^{a,c} for more than one year (see Section 6.1.1.3). For the most part, Type F seal dimensions and normal operational characteristics are unchanged from the Type C.

In the discussion of KSB seals, it should be noted that currently, KSB seals include one of two seal heat removal strategies. In the Type A and most Type C seals, heat removal included an external seal heat exchanger and small internal inter-stage coolers positioned at the pressure breakdown throttle devices between the Stages 1 and 3 and Stages 2 and 3. This arrangement was recently modified. The intent of

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[5] [ ]^{a,c}

this change was to "simplify the seal design" without compromising the seal's cooling capability or operational performance (Reference 6). The first seal design in Korea to utilize this arrangement was that of Shin Kori Units 3 and 4. This seal arrangement will also be used with the Type F seal for APR1400.

Discussion in Section 2.2 through Section 2.5 focuses on the design and expected nominal operational performance characteristics of the KSB RCP seals to be used in APR1400. Unless otherwise stated, the discussion seal design specifically applies to the Type F seal package.

2.2 SEAL DESIGN FEATURES

2.2.1 Seal Cooling During Normal Operation

The KSB RCP seal includes redundant means of cooling: (1) direct seal injection and (2) heat removal via the component cooling water (CCW) system. Either means of cooling will provide sufficient heat removal to enable continued seal operation for an extended time period.

During normal operation, both means of cooling are active. In the seal cooling process, cooling water from the charging system is directly injected into the RCP seal cooling loop where it passes through a RCP seal heat exchanger (high pressure cooler) see Figure 2-1. Fluid leaving the heat exchanger is directed into the seal. A small portion of the flow is directed into the seal package and the remainder is combined with a recirculation flow generated by an auxiliary impeller to provide cooling to the pump journal bearing in the upper portion of the pump. The second heat removal mechanism is by way of the CCW system. Cooling water from the ultimate heat sink is directed to the RCP seal heat exchanger. In the event seal injection is lost, pressure differences in the seal package will drive pressurized reactor coolant flow through the RCP seal high pressure heat exchanger. The heat exchanger will provide sufficient heat removal to maintain seal temperatures to acceptable levels for an extended period.[6] If cooling to the RCP seal heat exchanger is lost, abnormal operation seal experiments (see References 3 and 4) show that the relatively cold seal injection fluid is sufficient to maintain the RCP seal within its limits of operation.[7] Specifically, the test report concluded that the "pump will continue to function without seal leakage in excess of design limits". Similarly, extended seal operation is also possible following a loss of seal injection. Provided the fluid temperatures entering the seal package are maintained in the normal operating range, either cooling mechanism will enable continued seal operation for an extended time period. This capability has been confirmed via pre-operational testing performed by CE at PVNGS (References 3, 4 and 15), and more recently by Westinghouse for Shin Kori Unit 3 and Barakah units (References 5 and 12).

2.2.2 Seal Materials (Type F)

Key materials used in the Type F seals include upgraded (high temperature resistant) elastomers capable of withstanding long-term exposure to a high temperature and pressure environment. Recent tests of RCP seal O-rings employed in the Type F seal design indicate that the seals can successfully withstand

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[6] See Section 4.5.2.2 of Reference 7. While indefinite operation in this condition is possible, it is cautioned that such operation can potentially result in contaminants being directed into the seal package.

[7] Note that the KSB technical manual cautions against operation in this state with rotating pump for more than 10 minutes to avoid damage to the pump thrust bearings.

a,c

In addition to the use of qualified elastomers, the KSB HDD-254 Type F design is designed with Silicon Carbide (SiC) seal faces. SiC has also been used in the KSB Type C seal designs and has been shown to be resistant to abrasion and provides excellent high temperature performance. Current seals with SiC face material are estimated to have a seal lifetime of 48 months (Reference 6).

2.3 NORMAL TYPE F RCP SEAL OPERATION

Figure 2-1 presents a schematic of the operation of the KSB RCP seal. During normal operation, a 6 to 7.5 gpm seal injection inflow pushes approximately 3.2 gpm (12.1 lpm) up through the seal package. Additional cooling is provided through the CCW system. During normal operation, seal package temperatures are in the 150^{o}F (66^{o}C) range.

To limit leakage, the RCP seal flow passes through the high resistance PBDs (small diameter helical tube) and the flow resistance orifice (P275) in the CBO line. The tubes in the PBDs and orifice are designed to provide a pressure breakdown distribution in the three seal cavities (P01, P02, P03) with ratios of 0.42:0.42:0.16, respectively. The pressure in the uppermost stage is set by the staging flow resistance orifice (P275) and the pressure in the downstream volume control tank. This flow is also identified as CBO and represents the majority of the seal leak-off flow during normal operation. A small leak of less than ~3 gph (0.19 lpm) flow passes through the seal faces and passes as a thin film. This leakage enters a reactor drain tank (RDT). In addition, a very small flow can also pass up the shaft and into the reactor building (RB) if the RDT flowpath is not available.

a,c

Figure 2-1: Flow Diagram of KSB Type F RCP Seal[8] Hydrodynamic Shaft Seal System

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[8] Based on Reference 7. Note: optional HSS and PTCV arrangements are not shown.

2.4 ABNORMAL OPERATION

Operating guidance for the following conditions was developed by KSB (Reference 7)[9].

2.4.1 Total Loss of Seal Cooling

2.4.1.1 RCP Operating

In the event of a loss of seal injection and CCW heat removal capabilities, the operator is directed to isolate CBO/staging flow within one minute and trip the RCP within 3 minutes (Reference 7). Early isolation of CBO[10] extends seal package heatup time and ensures a cool seal. [ ]^{a,c}

Specifically, the KSB analyses indicate that provided the RCP is shut down and CBO is isolated immediately after a total LOSC and the RCS is maintained at the initial temperature, the heatup of the RCP seal package is conduction limited and will heat up over a period of 24 hours to ~[ ]^{a,c} The resulting heatup will cause the third stage RCP seal to asymptotically approach a temperature of [ ]^{a,c} see Figure 2-2 (Reference 9). At this temperature, long-term seal elastomer performance is assured. Testing performed by KSB confirms that seal package elastomers (i.e., O-rings) will continue to perform their function for at least [ ]^{a,c}. While seal integrity is expected, the RCP user manual cautions that operation of the RCP beyond 3 minutes after total LOSC may result in damage to the seal system and water lubricated journal bearing.

a,c

Figure 2-2: Temperature Variation of KSB Type F Seal as a Function of Time[11]

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[9] The specific guidance was prepared for the Shin Kori Units 3 and 4 Type C seal, but is considered applicable to the Type F as well.

[10] For purposes of this discussion, early isolation implies times less than 10 minutes.

[11] Type C seal is expected to have similar performance.

Delays in isolating CBO following LOSC increases the potential for seal heatup. Analyses assuming CBO is not isolated for the event duration indicates that seal stages will rapidly heat up reaching [ ]^{a,c} (see Figure 2-3), asymptotically approaching [ ].^{a,c}

a,c

Figure 2-3: Heatup of Type F RCP Seal, CBO Line Not Isolated[12]

Note that continued RCP operation without seal cooling can potentially damage the seal package possibly increasing seal leakage. Testing of seal package heatup in the absence of an extended LOSC has not been performed; however, anecdotal evidence from hydrodynamic RCP seals of similar design suggest seal packages can effectively maintain their ability to limit RCP seal leakage for time frames in excess of 30 minutes even when RCPs are not shutdown (Reference 1). This observation is likely a combination of factors including low initial operating temperatures, fluid transport considerations, residual mass in the RCP seal high pressure cooler, thermal capacitance of the seal package, and ability of seal and journal bearing components to withstand limited time exposure to high temperatures. For purposes of the assessment and for consistency with Reference 1, it is assumed that operation of the RCPs in the absence of seal cooling for a period in excess of 20 minutes will adversely impact RCP seal performance.

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[12] Type C seal expected to have similar performance.

2.4.1.2 RCP Idle (Hot Standby)

Additional manufacturer guidance is provided in the pump technical manual (Reference 7) noting that a RCP may be maintained for a period of 30 minutes in a hot standby following a LOSC condition provided CBO is isolated within one minute of RCP shutdown.

2.4.2 Seal Operation Following Loss of CCW

KSB RCP seals are designed with redundant RCP seal cooling systems. Failure of either the seal injection or CCW cooling to the RCPs will not impact the ability of the seal to perform. To this end, RCP seal demonstration tests have been performed by CE in support of the System 80 licensing. These tests included an early KSB RCP design with the KSB Type A RCP seal. Results of this test are included in CENPSD-201-A and CENPSD-201, Supplement 1-A (References 3 and 4). These reports provide analytical and experimental (prototypical) bases for confirming pumps can operate for a period in excess of 30 minutes following a loss of CCW to the RCP pump motor thrust bearings without causing damage to the seals or the pump, and the RCP will continue to function without seal leakage in excess of design limits.

Loss of CCW to the high pressure coolers only was also investigated to understand the impact of this event on RCP seal performance. Provided seal injection is maintained below ~[ ]^{a,c}, Reference 4, suggests that the RCP seal package will remain below its normal operational limit. The KSB technical manual requires shutdown of a RCP within 10 minutes of loss of CCW cooling.

2.4.3 Seal Operation following Loss of Seal Injection

Loss of seal injection has been investigated as part of the RCP acceptance test program. Loss of seal injection tests for KSB RCP seals have been reported in References 5 and 15. Tests were initiated from normal operating conditions, pumps continued to operate, and CCW cooling via the high pressure cooler was available. Results of this test confirmed the ability of the seal package to be maintained below its operating limit.

2.4.4 Degraded Seal Performance and Seal Leakage

Type F seals have been designed to have the same normal operational characteristics and very similar geometric arrangements as that for the Type C seal. Therefore, given a specified leakage configuration (e.g., one stage or more stages failed), the degraded leakage performance for the Type C and Type F seals is expected to be the same. In the case of catastrophic failure (i.e., all seal stages failed), the maximum leakage is controlled by the RCP thermal barrier geometry. Although the following information of this subsection is based on a RCP R01/Type C seal arrangement, the results and conclusions are applicable to a Type F arrangement.

Degradation of RCP seal capability can lead to increased flow of fluid through the PBDs (increased CBO) and potentially increased leakage to the RB. As each stage of the RCP seal is capable of retaining full RCS pressure, degradation/failure of the seal stages will not prevent the RCP seal from performing its function provided one or more stages remains operational. Plant staff routinely monitors RCP seal operation to confirm that stage pressures, CBO flow, and bleedoff temperatures are within operational limits. Typically acceptable pressure breakdown operation allows for a ±10% pressure drop variation across the seal faces.

In the event one or two seal stages fail, the CBO leakage will increase based on the location of the stage failure (see Table 2.4-1). In accordance with the RCP technical manual, the leakage will be limited to less than 10.1gpm (38.3 lpm) as long as one stage remains operational. In the event all seal stages fail to retain pressure (such as during a total LOSC event or SBO induced LOSC), seal leakage will significantly increase as the low resistance flow pathway is through the seal faces and the high resistance PBDs become bypassed. These leakages are limited by details of the high resistance pathways of the RCP thermal barrier, particularly in the region of the journal bearing below the RCP seal. [

]^{a,c}

Table 2.4-1: CBO Bypass Leakage Flowrates following RCP Seal Stage Failures (Extracted from Reference 7 for KSB Type C RCP Seals*)**

a,c

Failed Seal, Number	None	1 or 2	1 and 2	1, 2 and 3

2.5 APR1400 CONTROLLED BLEEDOFF OPERATION AND FLOWPATHS

The RCP shaft seals are operated in conjunction with two support systems: the RCP Seal Injection (SI) and CCW systems. The seals are supplied with filtered, chemically controlled seal injection water of [ ]^{a,c} per pump by the Chemical and Volume Control System (CVCS) and filtered recirculation seal injection water at a point below the water lubricated journal bearing, which is directed through the injector/cyclone assembly to the high pressure cooler before being injected into the seal system (see Figure 2-1).

The effluent from the high pressure cooler enters the high pressure side of the first seal and is divided into two flow paths. A majority of the flow is recirculated through the journal bearing by the auxiliary impeller and part of it passes into the RCS. This cools the journal bearing and minimizes the ingress of contaminants into the seal system from the RCS. The remaining flow enters the first seal and passes through a throttle coil (PBD) where the pressure is reduced before entering the second seal. Flow from the second seal continues through another throttle coil to the high pressure side of the third seal and then to the CVCS. The controlled bypass leakage around the seals is required to maintain the seal pressure breakdown.

a,c

For APR1400, seal injection water is supplied to the RCPs by charging pumps or an auxiliary charging pump. The auxiliary charging pump is used to provide seal injection water when two charging pumps are unavailable. The auxiliary charging pump is a positive displacement type, which is installed in parallel with charging pumps and powered by emergency diesel generators or by the AC Power Source (AAC) to maintain seal injection water under abnormal conditions.

Figure 2-4 illustrates the CBO flowpaths as the CBO flow exits the RCP seal package. The isolation valves of RC-430 (-431, -432, -433) provide the ability to fully isolate CBO flow for each RCP by the manual operation, as shown in Figure 2-4. The CBO may be isolated by the main control panel or in the field. Guidance is provided for CBO to be manually isolated within 1 minute in case of LOSC. No automatic isolation capability is provided. The CBO lines from the individual RCPs join in a common line, which contains the CBO air operated isolation valve (CH-506) and the CBO motor operated isolation valve (CH-507) to provide the ability to fully isolate CBO flow for all RCPs.

Note that this common line also includes a CBO relief valve (CH-199), which will lift to relieve pressure in the CBO lines, if the CBO isolation valve of CH-506 inadvertently closes. There is a CBO relief isolation valve (CH-507) between the CBO line and the CBO relief valve. The CBO relief isolation valve is a motor operated type and can be operated by the operator on the main control panel, remote control panel, or in the field.

a,c

a,c

Figure 2-4: Schematic Diagram for APR1400 CBO Line
(outside containment valve arrangements not shown)

2.6 IMPLICATIONS OF USE OF KSB TYPE C VS. TYPE F SEALS

As discussed previously, the general design of the Type C and Type F seals are similar. A comparison of the two seal designs are provided in Table 2.6-1. With the exception of secondary seal elastomers, these KSB seal designs share the same nominal dimensions, materials of construction, and operational parameters. As a result, the overall seal performance and nominal leakage performance under normal conditions is expected to be the same. However, the Type F seal incorporates design improvements that do not impact nominal seal operation while providing a seal more robust to high temperature challenges resulting in a lower probability of seal stage failure following total LOSC events.[13]

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[13] Two important differences between the Type F and Type C seals are: (1) Type F seal component part dimensions have been controlled to limit thermal stress during seal heatup, and (2) Type F secondary seals selection has been modified to improve the high temperature thermal resistance properties of the secondary seal elastomers. Both of these changes are intended to ensure a minimally distorted seal configuration can be maintained during high temperature SBO conditions for an extended duration.

Table 2.6-1: Comparison of Type F and Type C Seals

a,c

Feature	Type C	Type F

3 SEAL FAILURE MECHANISMS

This section provides a discussion of potential seal failure mechanisms associated with a loss of cooling to the RCP seals. Operational experience with various seal designs indicate that extended LOSC events are, in practice, the only initiating events which can threaten seal integrity. The susceptibility of the various seals to these failure mechanisms vary among the seal designs.

3.1 OPERATIONAL FAILURE MECHANISMS

WCAP-16175-P-A notes that industry-wide, many seal stage failures occurred during the early years following initial plant startups. Root cause analyses of these failures indicated that the majority of the failures were the result of faulty design, assembly, or maintenance. Several seal stage failures were attributed to a loss of cooling to one or more RCP seals. Other RCP seal failures can be classified as system-related, design-related, or maintenance-related.

- System-related failure causes include RCS fluid contaminated with metal chips, corrosion products, or other solid particles, thermal or pressure transients, low system pressure, faulty valve lineups, improper venting, and loss of cooling and/or loss of seal injection.
- Design-related and manufacturing-related failure causes include excessive wear, improper seal and face materials, heat checking, improper balance ratios, poor arrangement of elastomer seals resulting in deformation of shaft sleeve, arrangement of seals in such a way that reverse pressure (as during venting) can displace the seal from its intended orientation, sharp edges which cut the seals during installation, manufacturing defects, such as out-of-design-tolerance parts, poor quality assurance, and quality control.
- Maintenance-related failure causes include lack of proper training, lack of proper maintenance, inspection and testing tools, defective parts, wrong parts, missing parts, replacement parts from uncertified suppliers, wrong materials, improper lubricants, introduction of contaminants, lack of receipt inspection, improper instructions, poor drawings, doing maintenance under severe time constraints, and lack of quality control.

As plants matured, utilities learned how to treat the seals in such a way (both in maintenance and operation) as to maximize their useful life.

Over the past three decades, considerable operational history has been collected by KSB on the RCP seal performance of KSB seals. KSB notes in the performance of Type C seals have been excellent and that RCP seal has not resulted in a plant shutdown (Reference 6). A discussion of KSB RCP seal operational history is presented in Section 5.

The potential for operational seal stage failures to influence the seal failure probability is explicitly considered within the seal failure model as it may affect stage integrity prior to and during a LOSC initiating event (see Section 7).

3.2 SEAL FAILURE MECHANISMS DUE TO LOSS OF SEAL COOLING

The Brookhaven National Laboratory (BNL) report, “Guidance Document for Modeling of RCP Seal Failures” (Reference 10), identifies and models three seal failure mechanisms associated with Loss of Component Cooling (LOCC) Water events. These are:

- Binding failure of the seal ring
- Extrusion failure of secondary seal elastomers (O-ring Extrusion Failure)
- Opening of seal faces due to hydraulic instability (popping open) caused by fluid flashing.

The major concerns associated with the survivability of RCP seals during a LOSC are associated with the high temperature performance characteristics of polymers, used as secondary and primary seals, and the potential for hydraulic instability (popping open) of the primary seals when exposed to low subcooling and two phase fluid conditions. As will be discussed later, since the temperature and pressure may vary at each seal stage, the impact of these failure mechanisms can be different at each seal location. Therefore, since these failure mechanisms affect each individual stage differently, they must be evaluated for each stage. The following subsections briefly discuss each of these failure mechanisms.

3.2.1 Binding Failure of the Seal Ring

The seal rings normally move freely along the seal housing inserts. Binding occurs when the secondary seals exhibit premature extrusion induced by sustained high temperature conditions. Binding failure is a function of the design of the seal, selection of seal material and the duration of the temperature exposure of the seal. As the exposure time increases, the elastomers are postulated to soften and possibly extrude into the clearance gaps between parts of the stationary seal. This would result in additional frictional forces that would inhibit the motion of the stationary seal face. If the downward shaft motion, when exposed to the high temperature condition, tends to pull the seal open, the hydraulic closing forces may not overcome the jamming force associated with the extruded or softened seal material, and the seal stage would jam open. Seal motion may result from RCS pressure transients and/or thermal expansion of the RCP shaft possible during LOSC conditions. This would result in the seal gap opening up and providing a leakage path. Seal stage failures of this type have been observed with LOSC in hydrodynamic RCP seal designs employing Nitrile based elastomers. These elastomers are not intended for moderate and high temperature operation and are no longer used in the current generation of RCP seals.

The potential for this failure mechanism is a function of the temperatures reached in each seal stage, the elastomer material, the extent of the postulated extrusions, the seal restorative forces (hydraulic and mechanical) that would act to offset the additional frictional forces associated with seal degradation, and the degree and timing of shaft motion.

The impact of seal binding is limited by the travel of the RCP shaft. Shaft motion may arise as a result of thermal expansion of the shaft or RCS pressure changes. Binding failures are largely mitigated by use of high temperature resistant “qualified” elastomers.

3.2.2 Elastomer Extrusion

The primary seal consists of a rotating face and a stationary face per stage; these seals control the reactor coolant leakage flow that is required for lubrication. The secondary seals, consisting of elastomers of various forms depending on the seal design, serve to seal the points of contact between parts of either the rotating seal or the stationary seal which have limited motion relative to each other. These elastomers serve to prevent secondary leakage which would bypass both the primary controlled leakage path through the gap between the stationary and rotating seal faces and the CBO flow path. This is accomplished by sealing the points of contact between two metallic and ceramic seal components. The failure characteristics of O-rings depend upon temperature, differential pressure across the seals, and the seal geometry. The probability of O-ring extrusion failures increase significantly upon exposure to high temperatures, such as those associated with a LOSC.

Under LOSC conditions, the elastomers in each seal stage will experience increased temperatures and, depending on the properties of the specific elastomer, the elastomer may begin to soften and extrude into gaps between the seal parts. If the extrusion/deformation of the elastomer is sufficient to cause loss of its capability to seal the specific gap, then failure of one or more critical secondary seals could result in a secondary leakage path. Such failures could also perturb the normal pressure balances and component clearances leading to the increased potential for other failure mechanisms such as the binding mechanism discussed in Section 3.2.1.

The potential for the extrusion failure of the elastomers is a function of its material properties, seal component gaps, and the temperatures experienced. The pressure differential can also affect the degree of extrusion. Seal degradation by extrusion/binding can be significant for seals with non-qualified (i.e., low temperature resistant) O-rings. The KSB Type F seal package utilize EPDM O-rings and other elastomers with high temperature performance and are consistent with the BNL qualified O-rings. Consequently, the likelihood of seal stage failure due to extrusion of a secondary seal is very low. However, it should be noted that the failure potential will depend on temperature exposure, which has both a stage and operational dependency. The temperatures experienced in a given seal stage is a function of the stage location and the status of the CBO flow. In general, if CBO is not isolated following a LOSC event, uncooled RCS liquid will begin to flow into the seal package causing the seal stages to heatup, with the lower stages experiencing higher temperatures than the upper stages. If CBO flow is isolated early, the temperature in a given stage will slowly increase due to heat conduction from the RCS to the RCP seal through the RCP metal from the stage below it. This will be countered, at least in part, by heat conduction to the exterior of the seal shell and radiant cooling to the containment. In this situation, the lowest seal will experience higher temperatures than the upper seals.

3.2.3 Hydraulic Instability (Seal "Pop-open")

Fluid flashing within the RCP seal could cause hydraulic instability, which in turn can cause the opening of the seal faces due to the 2-phase flow phenomenon that alters the pressure distribution between seal faces. Factors that contribute to the hydraulic instability (pop-open) failure mechanism and how it might propagate from stage to stage is documented in Table 4.2-3 of Reference 1. Note, that these factors are applicable to all hydrodynamic RCP seal cartridge types, with the exception that the upper stage row of Table 4.2-3 of Reference 1 is not applicable to the 3 stage seal design.

Hydrodynamic seals are designed with a mechanical spring force and fluid pressure acting in unbalanced areas of the seal ring to provide seal face closure. During normal operation, the seal surfaces are separated only by a thin fluid film developed by the pumping action caused by the rotational velocity of one of the seal faces and the pressure gradient across the sealing gap. While the response of the hydrodynamic seal is robust to a wide range of subcooled fluid conditions, as the lubricating fluid approaches saturation, the fluid within the seal may "flash" (become partially vapor) creating a choked flow condition within the seal gap. Flashing in the gap will change the pressure distribution within the seal face. Analytical models developed by Atomic Energy of Canada Limited (AECL) (Reference 10) suggest that the resulting two phase pressure distribution within the seal will result in a larger net opening force on the seal. Under certain circumstances, this force can lead to a new, larger stable seal operating point (increasing seal leakage) or create an unstable condition leading to variations in the seal gap. The coined term describing such seal gap increases resulting from changing hydrodynamic conditions within the seal is seal pop-open. The seal pop-open process is reversible in that changing dynamic conditions will alter the loading, and increased flow through many seals would increase the seal backpressure which contributes to seal reseat. Acting in conjunction with elastomer extrusion and/or elastomer binding, seal pop-open may result in a sustained seal stage failure.

Hydrodynamic stability analyses of various seal designs indicate that the hydrodynamic response of RCP seals is influenced by several operational and design parameters. Specifically, analyses have shown that face seal will remain stable when:

- The inlet fluid is sufficiently subcooled [> 50°F (>27.8°C)], or
- The backpressure (P_b) acting on the seal is greater than half the saturation pressure at the inlet temperature

$$P_b > \frac{1}{2} P_{sat}(T_{inlet})$$

These conditions are generally sufficient to ensure that fluid flashing (necessary to create a pop-open condition) will not occur in the seal gap.

Analytic studies of Byron Jackson and Sulzer Seals (Bingham International) conducted by Rhodes indicated that the pop-open behavior of these seals was not likely at Stage 1, while coupling may be expected between Stages 2 and 3. It was also noted that test predictions using the Rhodes model for these codes indicated that even under SBO fluid conditions that would be indicative of pop-open, only the third stage was predicted to be unstable. While at the same time, no unstable seal performance was observed (Reference 10).

Intermittent and sustained seal pop-open events have been observed during tests of BJ Sulzer seals (see Section 6.0 of Reference 1). The pop-open behavior was often transitory and impacted only certain seals. This behavior is generally consistent with Rhodes' observations. Evidence of local seal pop-open has been noted in operational LOSC events at various CE PWR plants (see Section 7.0 of Reference 1). Generally, pop-open events have propagated to stage failures when extended exposure of seals to high temperature liquid aggravated the pop-open process by increasing shaft friction forces, making it more difficult for the seal to reclose once the dynamic condition has been removed. In the early 1980s, RCP manufacturers redesigned the RCP seal cartridge to be more robust to the adverse conditions following SBO events. KSB considers the likelihood of seal pop-open for Type F seal designs to be very low. To confirm their hypothesis, KSB conducted a pop-open experiment with the full scale HDD-254 Type F seal installed in the test facility. Subcooling on the stage 3 seal was reduced to near saturation conditions with the simulated RCP pressurized. No significant increase in seal leakage was noticed. This confirms that the Type F seal is resistant to the pop-open failure mode. A sensitivity study investigating the impact of potential reduction in pop-open risk is included in Section 10.2.

4 OPERATIONAL CONSIDERATIONS AFFECTING SEAL PERFORMANCE

In order to better understand the seal failure model presented in Section 7, several aspects of normal and abnormal seal operation and post-accident response of the plants to LOSC events should be highlighted. These items are described in the following sections.

4.1 PRESSURE STAGING AND CONTROLLED BLEEDOFF

a,c

4.2 SEAL LEAKAGE ASSESSMENT

The staging of the seals plays an essential role in controlling the RCP seal leakage. Catastrophic failure of a single RCP seal stage will result in the inability of the affected seal to maintain the staged pressure drop across the face seal. This failure, in turn, results in flow normally directed through the PBD to be redirected towards the low resistance path offered by the open (failed) seal stage. Consequently, the seals will restage, i.e., develop a new pressure breakdown. The loss of fluid resistance in the failed stage will result in an increased CBO flow. A complete stage failure will be sensed as a lack of ability of the seal stage to hold pressure.

Provided at least one hydrodynamic seal stage remains intact, the increased RCS leakage flow will be controlled to small levels by the non-bypassed pressure control devices internal to the RCP seal cartridge. Table 4.2-1 illustrates the expected increase in leakage for various combinations of failed seal stages. When the vapor seal is intact, the increased flow will be primarily directed towards the CBO line. Otherwise, when the vapor seal is failed, seal leakage will be noted and the excess flow will be directed to the containment. Estimates of increased seal leakage for partial seal failure (i.e., up to two seal stage[14]

a,c

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[14] As Type C and Type F seal nominal dimensions and operational behaviors are similar, both seals will exhibit similar leakage flowrates given stage failures. When all seal stages fail, leakage will be largely determined by design features of the RCP thermal barrier, and degree of failure of the RCP seal.

Table 4.2-1: Summary Impact of Stage Failures for the KSB 3-Stage Seal Design*

Stages Failed	CBO	Leakage to Containment	Comments

a,c

Note that seal leakage calculations assume the RCS is maintained at full pressure. As RCS pressure diminishes, so will the attendant leakage. This is well below the inventory loss necessary to cause incipient core uncovery. As a consequence, for this assessment, seal packages with fewer than all the internal seal stages failed are considered functional (not failed) for purposes of averting a seal induced LOCA.

4.3 RCP SEAL CONDITIONS FOLLOWING LOSS OF SEAL COOLING EVENT

Loss of cooling to the RCP seals can potentially subject portions of the RCP seal to a prolonged adverse operating environment. The actual conditions that the RCP seals will be exposed to following an event are based on both the details of the initiating event and the operator's response to that event. In order to understand the various impacts of LOSC events on seal performance, it is useful to understand the post-accident thermal-hydraulic performance of the RCP seal cartridge. This section explores the post-accident seal environmental conditions that would precede seal degradation.

For the APR1400 KSB pump/seal design, the seal heat exchanger cooling loop is supplemented by an independent seal injection system. In this context, LOSC applies to the total loss of cooling to the RCP seal and implies loss of both the CCW to the heat exchanger and loss of direct seal injection to the RCP seal.

The LOSC can occur in the following ways:

1. SBO (loss of offsite power (LOOP) and inoperability of all plant diesels) causing a total loss of all seal cooling.
2. Random or induced simultaneous loss of CCW and loss of the seal injection system or subcomponents or either system sufficient to result in failure of these systems to deliver cooling water to the RCP seals.

The impact of these events on operator actions and the post-accident seal environment is discussed below.

4.3.1 Seal Conditions during a Station Blackout Event

Both RCP seal coolant systems (injection and recirculation type) require power to operate the pumps to remove RCS heat from the seal. A SBO event implies a complete loss of AC power. SBO events will cause a loss of power to the RCPs, loss of seal heat removal and a reactor trip. During a SBO, heat removal from the RCS will be maintained as long as batteries are available to power the SG level instruments and turbine driven steam pumps remain functional.

With the exception of maintaining RCS heat removal via SGs during a SBO, operators have limited control of plant dynamics. Atmospheric Dump Valves (ADVs) and sufficient secondary side condensate will be available to affect a plant cooldown. Strategies for responding to SBOs will vary based on the cause and expectations of the duration of the event. Long duration SBO events have been defined in the context of an ELAP. In the case of ELAP, current APR1400 guidance instructs the operator to hold the plant at full RCS pressure and temperature for 8 hours. At which time the plant will commence a rapid cooldown to the SIT setpoint (see Reference 16). As the actual accident progression following ELAP is uncertain, the RCP seal model conservatively assumes long-term constant high temperature exposure. That is, credit for specific strategies is not explicitly included in the baseline RCP seal failure probability.

Closure of the CBO line during a SBO is accomplished via operator action in the control room. Closure of the CBO line will stop flow through the seal PBDs and equalize the seal cavity pressures at the level of the RCS pressure. [

]^{a,c}

a,c

addition, as a result of lower cavity pressures, temperatures in the vapor stage will be below that of the lower RCP seal stages. This factor is also important to take into consideration when estimating whether flashing may or may not occur at a particular seal stage.

Table 4.3-1 provides an approximate post-LOSC temperature distribution for a SBO condition with CBO not isolated. This temperature distribution is consistent with results of KSB testing (see Section 6.2).

Table 4.3-1: Approximate Type C/F Third Stage and RCP Seal Lower Cavity Equilibrium Temperatures Following Loss of Seal Cooling Event

a,c

a,c

Based on the above considerations, representative temperature distributions were developed for quantifying post-SBO seal environmental conditions associated with the coastdown of the RCS pressure and temperature. In developing Table 4.3-2 and Table 4.3-3, system pressures and temperatures were estimated based on results of KSB finite element RCP seal heatup analyses presented in Section 2.4.1.1, integral test facility results (see Section 5), and typical values associated with a plant depressurization strategy. For CBO not isolated cases, Stage 3 estimate pressure assumes the standard pressure breakdown ratio continues to apply.

Table 4.3-2: Representative Type C/F Post-Accident Conditions following a SBO Event

(RCS Pressure Assumed = 1,800 psia)

a,c

	CBO Isolated Early			CBO Isolated Late			CBO Not Isolated		

Table 4.3-3: 3-Stage Seal Design

Representative Type C/F Post-Accident Conditions following a SBO Event

(RCS Pressure = 1,300 psia)

a,c

	Pressure	**Temperature**	**Subcooling**	**Pressure**	**Temperature**	**Subcooling**	**Pressure**	**Temperature**	**Subcooling**

4.3.2 Seal Conditions during a Loss of Seal Cooling Event with Offsite Power Available

LOSC may be caused by a combined loss of seal injection and CCW. Under these circumstances, detection of global and partial loss of cooling events should be straightforward. Unlike events initiated with LOOP, LOSC with offsite power available do not automatically cause a shutdown of the affected pump. Before the RCP will be shutdown, one or more of the RCP trip setpoint parameters must be reached. These parameters are listed in Table 4.3-4. Note that operators are given advance warning that a trip setpoint is approaching. However, once the affected RCPs are secured, the operator has the full resources of the plant (that is, those resources not impacted by the initiating event) to manage the event.

Table 4.3-4: APR1400 Alarm and Trip Parameters for RCP (see Reference 7 for example, Type C/F)

a,c

Loss of CCW (LOCCW) events often affect components such as the RCP motor, which has similar temperature sensor indications.

Once RCP seal cooling has been confirmed to be lost, the operator is instructed to trip the affected RCP within three (3) minutes. Following RCP shutdown, the operators are further instructed to isolate CBO within one minute. For LOCCW events, the operator is instructed to ascertain the status of SI, and restore the other train of CCW. For pump running conditions, CBO is open. If LOCCW cannot be restored within 10 minutes, the RCP is shutdown. CBO is closed once the pump is idle.

Operator actions following RCP shutdown of importance to the seal conditions include:

- Diagnostic activity to assess capability to identify cause of loss and potential for restoration of cooling
- Actions for RCP shutdown and timing of CBO isolation in the event cooling cannot be returned promptly

Depending on the timing and success of the operator to shut down the RCP, thermal-hydraulic conditions within the seal package will vary. Note "Isolated Late" and "Not Isolated" temperature profiles assume a [ ]^{a,c}. Test data from the KSB full scale test indicates delayed isolation temperature differences between stages will be closer to [ ]^{a,c}. Third stage "Not Isolated" temperatures are based on that stage achieving a saturated condition consistent with the pressure distribution assuming a 0.42:0.42:0.16 seal stage pressure breakdown. Third stage conditions for the other isolation conditions are representative of typical expected seal heatup. The precise range of these values is not critical for the assessment of seal operational risk.

As indicated in Table 4.3-5 and Table 4.3-6, operator actions could substantially impact seal conditions. In situations when the CBO is isolated, the seal pressure will uniformly increase throughout the seal to near RCS pressure levels. When CBO is isolated early, this action also tends to ensure a high level of subcooling is maintained at the stage seal faces and eliminates the pressure drops across the internal stage seals. Both factors contribute to enhanced hydraulic stability of the seals and minimize the potential for seal failure due to the seal stage pop-open phenomena.

Table 4.3-5: Representative Type C/F Post-Accident Conditions following a LOSC Event Depressurized To 1,500 psia

a,c

Table 4.3-6: Representative Type C/F Post-Accident Conditions following a LOSC Event Depressurized To 1,200 psia

a,c

4.3.3 Impact of Seal Restaging on Seal Stage Environment

When CBO is not isolated, failure of one or more seal stages will cause one or more PBDs to be bypassed. The impact of this is to redistribute the RCS pressure reduction across fewer PBDs. In a 3-stage seal design, internal stage failure of one stage will redistribute pressure as shown in Table 4.3-7[15].

Table 4.3-7: Example Approximate Type C/F Pressure Redistribution in a 3-Stage Seal (RCS at 1,800 psia)

a,c

In either case, an internal seal failure will result in a lower pressure at the entrance to the middle seal stage. When this is the intact seal, the entrance subcooling will decrease. In the LOSC example, the entrance conditions will become saturated. On the other hand, when Stage 2 fails in advance of Stage 3, the downstream cavity fluid becomes pressurized increasing the seal stability.

The impact of pressure redistribution impacts the seal stage failure propagation and common cause conditions. Note that once Seal Stage 3 has failed, the probability of failure of Seal Stage 2 is increased as its subcooling margin will decrease.

A Stage 3 failure will direct additional CBO leakage into the seal leakage collection chamber where it will either drain into the radwaste system tanks or leak into containment through the throttle bushing.

4.3.4 Post-Accident CBO Relief Valve Operation and CBO Restaging

CBO flow isolation after the pumps are tripped will minimize the heatup rate of the seal cartridge. As shown on Figure 2-2, the CBO line has a relief valve and a relief valve isolation valve in a branch line upstream of the CBO isolation valve. In order to fully isolate CBO flow, both the CBO isolation valve (CH-506) and the CBO relief valve isolation valve (CH-507) must be closed.

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[15] Pressure distribution based on 0.42:0.42:0.16 pressure difference ratios between stages one, two and three. That is ΔP_{stage1}: ΔP_{stage2}: ΔP_{stage3} is 0.42:0.42:0.16

4.3.5 Comments on Event Duration and Cooldown Strategy

Event duration may impact seal failure probability. The extent to which this impact will occur will depend on the resources available to the operator in responding to the LOSC/SBO event and operational strategies the operator takes and duration of the event. From a seal capability perspective, high temperature exposure of O-rings materials will cause them to degrade over time. Short duration exposure of seals to high temperature may impact long-term applications of the elastomers, but not necessarily create a condition which will lead to a seal package failure. As high temperature exposure time increases the possibility of elastomer damage causing a seal stage failure increases. KSB notes that the with early isolation of the CBO staging flow following a loss of cooling to the seal, the seals will be kept at low temperatures and extended operation may be possible.

[

]^{a,c}

4.4 RCP SHAFT MOTION

As discussed previously, exposure of polymer seals to high temperatures may result in softening and extrusion of the elastomer. This change in properties and geometry may result in high friction forces and prevent the stationary portion of the shaft from following axial movements. Axial shaft movements occur as the RCS depressurizes and the RCP shaft moves downward, shifting from the upper to lower thrust bearing, or simply as a result of thermal expansion of seal and RCP components. This impact of pressure induced shaft motion is negligible above RCS pressures of [ ]^{a,c}

4.5 OPERATION OF THE RCP SEAL WITHOUT COOLING WHILE THE RCP IS IN OPERATION

The RCP seal model assumes that a total LOSC event in the presence of an operating RCP will result in seal damage if RCP operation is continued in excess of 20 minutes. This failure is generally assumed to be caused by instabilities associated with the RCP shaft resulting from breakdown of oil lubricating the pump shaft. Analyses and proof of concept experiments performed for an early KSB pump (see References 3 and 4) provide evidence that RCP seals should be capable of maintaining seal integrity for at least 30 minutes.

A LOSC event at Fort Calhoun Station (FCS) provides anecdotal information that indicates shaft operation, and seal integrity may be sustained for over 45 minutes. In the early 1970s, FCS, a CE-design PWR, experienced a loss of seal event that went undetected for 45 minutes. RCPs operated throughout the event. No increase in seal leakage was noted (see Section 8 of Reference 1).

4.6 FAILURE OF RCP MOTOR

Loss of CCW may result in loss of cooling to the RCP motor. The ability of the pump motor to survive an extended loss of cooling is not well understood. Some utilities have postulated that, given a loss of CCW, failure of the RCP motor may occur prior to RCP seal cartridge failure. However, loss of CCW to RCPs has been tested for the System 80 RCP motors and they were able to survive a thirty minute interval with no cooling. RCP motor performance tests were also included in the San Onofre Nuclear Generating Station (SONGS) BJ/Sulzer seal experimental test program (see Reference 1). These tests confirmed acceptable motor performance for a period of more than 20 minutes after loss of cooling water. Fort Calhoun operated their RCPs for a period of 45 minutes without seal cooling and did not experience a motor failure. Given this information, APR1400 does not credit failure of the RCP motor as a means of stopping the RCP given loss of CCW.

The KSB recommended operating limit for the RCP motor is only a few minutes without cooling water (see paragraph 2.3.5 of Reference 7). The motor bearings generate a large quantity of heat, which is removed from the bearings by the lubricating oil. This oil is cooled in heat exchangers, which depend on cooling water to function. If the supply of cooling water is lost, the oil temperature rises and the bearing surface temperature also rises. Oil quality (and therefore its lubricating properties) degrades at high temperature. The bearings are normally faced with Babbitt, a lead alloy material with a fairly low melting point. Given a loss of cooling to a KSB pump motor, References 3 and 4 indicate that temperatures in the vicinity of the thrust bearing Babbitt[16] material will not challenge RCP operation for a period in excess of 30 minutes (see also Section 4.5).

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[16] Babbitt metal is a soft and easily damaged material often used for a bearing surface liner.

5 KSB RCP SEAL OPERATING EXPERIENCE

KSB RCPs operated throughout the world; however, detailed operating experience is not available for all installations. Considerable information is primarily available from a number of German plants with close relationships to KSB. Limited information is also available from Korean operation. The following sections indicate the general experience of operation of KSB RCP seals.

5.1 OPERATATING EXPERIENCE IN THE UNITED STATES

The CE System 80 units at PVNGS were designed for operation with KSB pumps and KSB seals. However, KSB RCP seals have only been in operation in the United States through the early 1990s. During that time, three RCP seal related events were recorded at PVNGS. These events involved the Type A KSB seal. These events were discussed in Reference 1. A summary of these events, extracted from Reference 1, is presented in Table 5.1-1. These events indicate that the early version of KSB RCP seal (Type A seal) subjected to LOSC events can result in an increase in seal leakage. These events include both a total LOSC (intermittent) with short duration RCP operation and delayed CBO isolation, and a loss of site power (LOSP) event with a simultaneous loss of all seal cooling (90 minutes). Following the event, it was noted that “One of four pumps exhibited failure of Seal Stage #3”. All RCP seals were replaced following the event. As the KSB Type A seal at PVNGS was replaced by the Sulzer RCP seal in the early 1990s (prior to the resolution of GSI-23), no relevant data exists in the United States with respect to Type C seals (or any other later generation KSB seal).

Table 5.1-1: CE Plant Operating Events Leading to Loss of RCP Seal Cooling
(excerpted from Reference 1)

a,c

Table 5.1-1: CE Plant Operating Events Leading to Loss of RCP Seal Cooling
(excerpted from Reference 1)

a,c

5.2 OPERATING EXPERIENCE IN GERMANY

KSB seals have been in continuous operation in Germany since the 1970s. Type C seals have been the primary KSB reactor pump seal since the mid-1980s. Since the mid-1980s, no seal failures have been recorded. A more thorough review of the data was desired to understand the extent of potential stage failures and degradations that may have occurred. However, detailed records are only available for a few plants. This assessment consisted of a review of KSB maintenance and inspection records for seven (7) KWU (Kraftwerk Union AG), now Areva, plants in Europe. Those plants keep in close contact with KSB AG and KSB Service, which enables KSB to reproduce the complete lifetime of the RCPs especially with respect to any seal issues. Only performance data from Type C seals were evaluated. The reactors reviewed included Konvoi and pre-Konvoi plants. Characteristics of the analyzed data pool are as follows:

[ ]^{a,c}

Reference 22 indicated the average operational life of a RCP Type C seal prior to replacement was [ ]^{a,c}.

Overall performance of the KSB Type C seal has been excellent:

- Only a small number of distinct seal issues have been experienced
- None of these issues led to a reactor trip or unplanned outage of the plant
- No seal system failure has been experienced
- No total seal stage failure has been experienced
- No leakage to containment has been experienced

A minority of the issues related to seal performance can be attributed to the seal design itself. The primary issues identified based on plant experience in Germany provided to Westinghouse by KSB are summarized in Table 5.2-1. Of particular note is the conclusion that no total seal stage failure was noted to occur.

Table 5.2-1: Summary of Limited Scope KSB RCP Type C Seal Performance Data

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In establishing seal stage failures for the seal reliability assessment:

- Binding degradations due to improper lubrication were not considered as credible failures going forward since this issue has been resolved and proper grease and associated cautions were provided to the utility and staff.

- Handling failures were discounted as the failures occurred as new protocols for seal handling were established.

Based on information provided, no seal stage failures were noted. Potential degradation mechanisms were assigned to the excessive wear and unknown causes. Wear issues would be lower for Korean PWRs as the Korean RCP shafts rotate at 1,200 rpm compared to 1,500 rpm in German PWRs (Reference 6).

5.3 OPERATING EXPERIENCE IN SOUTH KOREA

CE-KSB Type R01 RCPs have been in operation in Korea since the mid-1980s. Initial RCP seals used in those plants were the HDD-254 Type A. Type C seal designs using SiC seal faces were introduced to the Korean fleet with the Shin-Wolsong Units 1 and 2 and Shin-Kori Units 1 and 2. Type C seals are also included in Shin-Kori Units 3 and 4.

Overall, the operational performance of the KSB RCP seals in Korea has been excellent. In the time frame between 1994 and 2013, over 3.5 million RCP run hours were accumulated on 44 RCPs (Reference 13). The fleet of RCPs has demonstrated excellent operating performance without a single seal stage failure reported.

It should be noted that up until the Shin Kori 3 and 4 designs, Korean unit RCP seals included the inter-stage cooler heat exchangers. Recently, as an enhancement to the KSB RCP seal design used for Shin Kori Units 3 and 4, the throttle coils were removed from the seal cooler. Reference 6 provides a discussion of the Shin-Kori Units 3 and 4 RCP 48 month shaft seal life report. This report specifically documents the performance of the Silicon Carbide-Carbon Compound seals (KSB Type C)[17] in Shin Kori Units 3 and 4. The conclusion of this report was that the current seal design (with throttle coils removed from the seal cooler) has a similar performance and the same 48 month expected lifetime as the earlier version. It was also noted in that report that no KSB type RCP seal failures have occurred in the Korean units. Seal pressure and temperature parameters are monitored to ensure proper stage operation.

No total loss of seal failure events have occurred on the Korean units; therefore, there are no operational events in Korea to confirm seal heatup performance during these conditions. Five events associated with partial loss of seal injection of short duration reduction have occurred while the plant was at power. All events resulted in restoration of seal injection within 1.1 hours, with most events lasting under 7 minutes. One event resulting from a failure of seal injection control valve diaphragm resulted in a small increase in seal injection flow. LOSC experiments on a prototype Type F seal are presented in Section 6.

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6 TESTS OF SEAL PERFORMANCE FOLLOWING LOSS OF SEAL COOLING

The intent of this section is to summarize the relevant information associated with the post-event performance of the KSB RCP seal and it associated sub-components.

6.1 SUMMARY OF RELEVANT RCP SEAL SEPARATE EFFECTS EXPERIMENTS

6.1.1 Experiments of Elastomer Survivability

Reference 1 noted that several experiments had been conducted to assess the temperature response of O-rings and other elastomers used in RCP seals. Insights generated from these tests are summarized below. In addition, information related to qualified elastomer tests performed in support of Westinghouse and more recent testing performed by KSB for Type F seal elastomers are also provided. This additional information has been used to inform seal elastomer failure parameters for use in the KSB RCP seal model (see Section 8). Section 6.1.1.1 summarizes results presented in WCAP-16175-P-A; Section 6.1.1.2 provides results from O-ring elastomer testing presented in WCAP-10541 (Reference 11) and Section 6.1.1.3 provides results from KSB HDD-254 RCP seal Type F specific elastomer O-ring testing (Reference 16).

6.1.1.1 O-Ring Static Seal Performance under LOCCW to RCP: Summary of WCAP-16175-P-A

The primary objective of the San Onofre test program reported in Reference 1 was to determine the response of static sealing O-rings used in the Bingham-Willamette Company's mechanical seal cartridge at SONGS to extended exposure to a high temperature and pressure environment. The tests were intended to bound the potential seal exposure following a LOCC. These tests were contracted by Southern California Edison and conducted by Kalsi Engineering, Inc.

The experimental program consisted of three test series. The tests were performed in a specially designed fixture which duplicated the exact gland dimensions of the full-scale seal cartridge. Each test series was conducted for a period of 8 hours. All tests were performed at a 2,250 psig nominal pressure. Each test included two different size seals and backup ring. Each of the O-ring seals were subjected to three temperature environments: 550°F, 600°F, and 650°F (288°C, 316°C, and 343°C, respectively). In addition, seal "hardness" measurements were also performed on 1-inch segments of the seal faces. The following discussion is extracted from Reference 1.

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Figure 6-1: KSB Type F Elastomer Exposure Profile (High Temperature Exposure Test)

6.1.2 Experiment Related to Seal Stage Pop-Open Behavior

The seal pop-open failure mode arises as a result of a hydraulic instability between the real face loads (forcing seal faces apart) and the seal spring restoring forces that act to limit the seal gap size. This instability has been observed in past experiments of hydrodynamic seals when the fluid entering the seal is close to saturation and the downstream pressure drop in the receiving seal cavity is less than half of the saturation pressure of the incoming fluid. Such conditions are consistent with significant flashing and choking of the fluid within the real gap. This is further discussed in Section 3.2.3 and Reference 10.

The pop-open failure mode may be impacted by seal design since pop-open failures tend to be created by seal instabilities that are driven by the seal-specific balance ratios and details of the seal gap (e.g., degree of divergence/convergence of the seal face). KSB has designed the Type F seal to be resistant to pop-open behavior. KSB performed low subcooling seal testing to establish the potential of these conditions to create pop-open conditions as part of the KSB Type F seal integral test program (see Section 6.2.2).

6.2 KSB INTEGRAL SEAL EXPERIMENTS

Integral seal package tests have been performed for several seal designs (Reference 21). These tests spanned a range of off-normal conditions from loss of major cooling to partial and complete LOSC simulations. Details of the 4-stage LOSC experiments have been discussed in Reference 1. As KSB seals were not in operation in the United States by the time the TR was written, discussion of the KSB seal test program was limited. This section expands the Reference 1 discussion on integral tests to include partial LOSC experiments (i.e., loss of CCW to RCP seals or loss of RCP seal injection) performed as part of the KSB RCP seal pre-operational test programs and results from full scale LOSC experiments performed with the KSB HDD-254 Type F seal.

6.2.1 Results of Pre-Operational Testing

Operational RCP tests are conducted as part of the 500 hour endurance testing or shorter duration proof of concept tests. These tests may be focused to confirm specific performance issues. This section summarizes results of relevant loss of cooling water and loss of seal injection tests.

6.2.1.1 Loss of CCW Tests (pump running)

The KSB RCP seal includes two cooling mechanisms. CCW is directed to the high pressure cooler that removes heat from the recirculated RCS water which is driven by and mixes with the seal injection flow and direct cooling via seal injection. To confirm the ability of RCP seal to be cooled via seal injection alone, a LOCCW event was simulated in the initial 500 hour PVNGS test program with Type A seal (Reference 15) and the Shin Kori Unit 3 (Reference 5) and Barakah nuclear power plants with Type C RCP seal (Reference 12).

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6.2.1.2 Loss of Seal Injection Tests (pump running)

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6.2.2 KSB Integral Test Program

In order to confirm the SBO coping capability of the Type F seal, KSB has embarked on a full scale integral seal test program. The test program was completed in 2016. The primary focus of the integral test was to demonstrate the integrity of the seals under expected ELAP conditions over a period of 120 hours.

The test program included three tests. Two tests were focused on demonstrating ELAP performance for an integral RCP seal package. A third test was focused on demonstrating the robustness of the Type F seal-to-seal pop-open processes. Both SBO experiments were performed using elastomers in the mechanical seal that were thermal-aged and irradiated to simulate the material degradation of 10 years operation. To simulate prototypical ambient conditions, the RCP seal package was positioned within the test facility in an enclosed shroud (see Figure 6-2). A schematic of the test facility is presented in Figure 6-3. Details of the KSB test program for the HDD-254 Type F RCP Seal can be found in Reference 21.

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Figure 6-2: Schematic of KSB RCP Seal Integral Test Facility

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Figure 6-3: Schematic of Test Facility and Instrumentation

6.2.2.1 Test 1: Integral Seal ELAP Test with Delayed CBO Isolation

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Figure 6-4: SBO Temperature and Pressure Steps for Test 1

6.2.2.2 Test 2: RCP Seal ELAP Test with Early CBO Isolation

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6.2.2.3 Test 3: Seal Pop-Open Effects Study

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6.2.2.4 ELAP OPERATION AND SEAL TEST RESULTS

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[18].]^{a,c}

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Figure 6-5: Stage 3 Conditions during Pop-Open Test 3

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[18] Modifications to the test facility were necessary to establish low subcooling conditions.

7 RCP SEAL FAILURE MODEL

The model for seal failure presented in this report includes an assimilation of information from several sources including the BNL Technical Report "Guidance Document for Modeling of RCP Seal Failures" (Reference 10), Reference 1, which includes a review of data obtained from RCP seal integrity experiments conducted by Byron Jackson and Bingham-Willamette, now Sulzer pumps, and results of recent tests performed by KSB regarding their Type F seal and associated seal components.

The RCP seal failure model includes two basic models: an environmental conditions event tree (Figure 7-1) and a 3-stage seal fault tree (Figure 7-2). The environmental conditions event tree is used to establish the value of key input parameters defining the basic events in the RCP seal failure fault tree. The model as presented is for failure of a single RCP seal (all stages) given LOSC to that seal. It is the responsibility of the utility implementing this model to ensure that it is correctly applied for all RCP seals impacted by a given initiator.

The RCP seal failure model predicts the probability of RCP seal failure given an initiating event resulting in a total LOSC and a course of operator actions. Essentially, the advent of a RCP seal failure becomes a complex delayed LOCA event initiator. Additional factors associated with the availability of mitigating equipment and post-LOCA decompression must be considered in order to follow this event to a core damage condition. Such models are generally available in plant PRAs. Section 8 describes the selection of values for the seal parameters for the PRA model. Section 9 provides RCP seal failure model quantification.

7.1 ENVIRONMENTAL CONDITIONS EVENT TREE

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Figure 7-1: Event Tree

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Figure 7-2: Fault Tree

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7.2 RCP SEAL FAILURE/LEAK MODEL (FAILURE MECHANISMS)

Once the environmental conditions are established, the conditions are transferred to a fault tree model to assess the potential for and magnitude of a RCP seal failure.

The KSB seal design relies on a 3-stage hydrodynamic seal. Failure of one or more RCP seal stages results in increased leakage from the RCS. However, analyses indicate that all seal stages have to fail prior to the onset of significant leakage from the RCS. Figure 7-2 presents the integrated CAFTA 3-stage seal fault tree model for failure of the seal. The model captures the combinations of RCS subcooling and timing of CBO isolation. Detailed seal model stage fault trees are represented in Figure 7-3 through Figure 7-5. The model includes mutually exclusive events limiting the number of pre-existing stage failures. Technical specifications typically allow continued RCP operation provided that no more than 1 seal stage failure per RCP has occurred. It is assumed plants will shut down if a second stage fails; therefore, multiple pre-existing stage failures are mutually exclusive.

The seal model considers three (3) elements. Four (4) failure mechanisms are considered for each element. These are pre-existing failures, elastomer failures due to high temperature exposure, hydrodynamic instability and random failure. Each of these failures is represented by a stage-specific basic event. A common cause effect was included in the model because of the interrelationship between the internal conditions of the lower stage seals in response to an upper stage seal failure. For example, failure of the third (upper) stage seal would expose the second (lower) stage seal to different thermal and saturation conditions. The model also limits the number of pre-existing seal stage failures to one through application of a mutually exclusive gate. Extended plant operation with more than one degraded RCP seal stage is considered unlikely. Quantification of these basic RCP seal failure model is presented in Section 9. Quantification of the RCP seal failure model with a degraded stage is presented in Section 10.6.

Failure of all seal stages implies the onset of a small LOCA. No significant leakage is assumed to occur so long as one of the three stages is intact.

Figure 7-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 1 of 4)

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Figure 7-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 2 of 4)

a,c

Figure 7-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 3 of 4)

a,c

Figure 7-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 4 of 4)

a,c

Figure 7-4: Model for Failure of 3-Stage RCP Seal Given CBO Not Isolated (Sheet 1 of 2)

a,c

Figure 7-4: Model for Failure of 3-Stage RCP Seal Given CBO Not Isolated (Sheet 2 of 2)

a,c

Figure 7-5: Model for Failure of 3-Stage RCP Seal (Mutually Exclusive Events)

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7.3 ADDITIONAL CONSIDERATIONS

7.3.1 Comments on Failures of Multiple RCPs

The seal failure models developed in the previous sections are constructed for estimating failure of a single RCP seal cartridge. The total leak rate from all pumps with failed seal cartridges must be determined to establish core uncovery. Section 4.2 presents predicted seal cartridge leak rates for a various number of failed stages. Significant RCS leakage flows are not encountered until all RCP seal stages have failed.

Failure of all stages (including the vapor stage) results in potentially large RCS leakages. Therefore, the time for recovery actions is dependent on the number of RCP seal cartridges failed. Neglecting the impact of increased seal leakage (associated with non-failed seal cartridges) the available plant recovery time is inversely proportional to the number of RCP seal cartridges assumed failed.

When multiple RCP seals are exposed to the same environmental conditions, the probability of multiple RCP seal cartridge failures should include a common cause factor to address the potential impact of common conditions. Engineering judgment is used in conjunction with the available operating experience associated with LOSC events in the United States (Reference 1) to estimate a common cause factor, Γ, which represents the probability that all affected RCP seals fail given that one of the affected RCP seals fails.

Reference 20 includes a summary of the LOSC events at CE PWRs in the United States that impacted multiple RCPs. Failure events occurred in the time frame from 1974 to 1989. During that time, 9 events were identified. Event times varied from a few minutes to approximately 4.5 hours. One of the two events lasting more than four hours resulted in a failure of seal stages on multiple pumps. One of 8 events that lasted more than 0.5 hours may have also resulted in a multiple RCP seal stage failure event (reported data was unclear). Based on this limited information, a bounding set of common cause factors were developed.

Common cause failure factors for multiple RCP seal failures given the failure of one RCP seal are extracted from Reference 1. In accordance with Reference 1, because of the time dependent thermal aspects of the seal failure mechanisms, the potential for common cause failure of the seals are judged to be relatively low early in the event but will increase as the exposure time increases. Using engineering judgment in conjunction with the operating experience data in Reference 1 (discussed above), the following Γ factors are used to estimate the potential for common cause failure of all RCP seals affected by a loss of cooling event given that one RCP seal fails:

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These common cause failure factors can be applied to a plant level model addressing multiple RCP seal cartridge failures. The associated time to core uncovery will vary depending upon the number of RCPs assumed to have failed seal cartridges, operator actions to depressurize the RCS, and inventory addition capability. These features are not addressed within the scope of this report.

Note that the common cause factors are set such that RCP seal failures that occur 4 hours or more following an unmitigated LOSC event assume an extremely high common cause factor (≥ 0.9) that all RCP seals will be similarly impacted, and the associated leakage applied to all affected seals.

8 CALCULATION OF THE RCP SEAL FAILURE MODEL PARAMETERS

This section provides the basis for quantification of the KSB Type F RCP seal failure model presented in Section 7. Specifically, the model parameters discussed are those directly associated with the mechanistic RCP seal failure modes associated with a LOSC including consideration of the time varying influence of the local seal stage environments. Model parameters are a function of the seal design, and to some extent, are therefore seal design specific.

The current model focuses on the quantification of the seal failure probability given a LOSC. It is not the intent of the present model to address the selection of plant operational parameters associated with the onset of LOSC events or the associated post-accident operator actions. These parameters are plant-specific and should be reflected in the plant PRA. The impact of these parameters may be significant as they affect the relative probability of experiencing various post-accident seal environments. This present quantification also does not consider recovery actions that may be implemented following the onset of a RCP seal LOCA.

8.1 GENERAL APPROACH TO FAILURE MODEL QUANTIFICATION

As discussed in the previous sections, RCP seal failure potential is strongly influenced by post-initiator RCS conditions and duration and magnitude of the seal exposure. The four external parameters of interest are (1) whether the RCPs are tripped within 20 minutes, (2) whether the CBO is isolated before significant heatup of all seal stages occurs, (3) whether the subcooling in the RCS is greater than or less than 50ºF, and (4) the time period that the seal stages are exposed to the thermal transient. This information is used to determine the values for the individual parameters used to quantify the seal stage failure probability for each seal stage and the overall seal failure probability. In addition, common cause relationships must be defined at various seal stages.

This section provides the basis for the quantification of the RCP seal model. The model consists of two parts: (1) a RCP seal environmental conditions event tree and (2) a RCP seal failure fault tree. The RCP seal condition event tree provides fundamental information for estimating the operating environment (thermal hydraulic conditions) for the various seal stages. These conditions are impacted by the category of initiating event, its duration and various operator actions including operation of CBO, and maintenance of subcooled margin. This information will establish the stage dependent severity of the seal challenge.

The fault tree defines the manner in which a RCP seal may fail. Failure is defined as the inability of all RCP seal stages (including the vapor seal) to retain RCS pressure.

The fault tree reflects both random and event-induced RCP seal stage failures initiated from an event that initiates a complete loss of RCP seal cooling. These events typically include the LOSC or a SBO. The difference between these events is tied to the impact of the initiating event on RCP operation. LOSC events may occur with an operating RCP. SBO events involve a LOOP which concurrently results in loss of power to the RCPs.

The Seal Stage Failure Event (SFOON) is comprised of 4 independent failure mechanisms:

1. Stage failure due to elastomer binding and extrusion (ELASN)
2. Random failures of a RCP seal stage during the event interval (RFN)
3. Failure of the RCP seal stage due to stage seal pop-open phenomena followed by a seal binding condition that prevents seal face reclosure (PON)
4. Pre-existing failure of a RCP seal stage (TMN)

The final N refers to seal stage number, with N=1 being the seal stage closest to the RCP and N=3 being the vapor seal stage for a 3-stage RCP seal. Seal failure is assumed to occur when each seal stage is failed (SFOON). That is, for a given RCP,

$$\text{Probability of RCP seal failure} = \prod_{N=1}^{N\,=\,\text{total stages}} (\text{SFOON})$$

As a result of the seal design, many of these stage seal failure processes are independent. The pop-open phenomena is tied to the level of subcooling upstream of each seal stage. As a result of seal operation and design, in many instances the seal stages are actually exposed to different thermal-hydraulic environments during the same LOSC event. For example, the pop-open failure of the seal stage closest to the RCS is governed by the RCS subcooling, while the upper seal stages may be exposed to seal cavity conditions near saturation. In the 3-stage seal design with CBO not isolated, the stage most susceptible to pop-open is Stage 3, which has both high local temperature and low system pressure. A pop-open of Stage 3 would cause the internal pressure to re-distribute, thereby reducing the subcooling at Stage 2 and increasing its pop-open potential. This was treated as a common cause effect in the fault tree modeling structure.

A second interesting note to the model is the impact of exposure time. Based on a review of actual RCP seal events, a strong correlation exists between the time of exposure of the seal stage to a high temperature environment and its propensity for stage failure. This feature has been included in the model as well.

8.1.1 Calculation of Model Parameters

Calculation of the RCP seal model parameters requires use of appropriate RCP seal success and failure data. For the KSB Type F seal design, seal performance data used for the model includes applicable information from Reference 1 supplemented by relevant KSB Type C seal operational experience (see Section 6.2) and recent KSB Type F seal experimental data. KSB Type C seal operational experience is relevant to the random (RFN) and the pre-existing (TMN) failure mechanisms. KSB Type C seal operational experience could not be applied to the elastomer binding and extrusion (ELASN) or the stage seal pop-open (PON) failure mechanisms.

8.2 CALCULATION OF RCP SEAL FAILURE PARAMETERS

The RCP seal stage failure mechanisms considered for evaluation includes:

1. Stage failure due to elastomer deterioration and extrusion (ELASN)
2. Random failures of a RCP seal stage during the event interval (RFN)
3. Pre-existing failure of a RCP seal stage (TMN)
4. Failure of the RCP seal stage due to stage seal pop-open (PON)
5. Vapor stage leakage sufficient to restage lower stages (VSLEAK)

In the naming convention provided above, the "N" indicates for which stage the failure element is applicable.

Failure mechanisms ELASN, RFN, TMN, and PON are modeled as separate inputs to each of the three seal stages under an AND gate requiring all three stages to fail before failing the seal.

Failure mechanism VSLEAK was modeled by establishing a leakage rate probability event that represents vapor stage leakage large enough to restage the lower seals. This VSLEAK event is modeled as an input under an AND gate that includes a similar seal failure AND gate capturing the ELASN, RFN, TMN, and PON failure mechanisms. However, given that the vapor stage leaks, the probability of elastomer failure in the vapor stage will be lower due to lower saturation temperature conditions on the vapor seal as compared to the CBO isolated case. Therefore, for the VSLEAK case the failure rate of the third stage due to elastomer deterioration and extrusion (designated by parameter ELAS3R) is based on values for elastomer failure of the third stage (ELAS3) for the CBO not isolated case.

The focus of this evaluation is on the Type F seal. Type C operating data can be used to estimate seal reliability under normal operating conditions (failure parameters RFN and TMN). Under those conditions, both seals are expected to have similar (if not identical) operational performance attributes. Type C operating data cannot be used to estimate seal reliability under abnormal conditions (failure parameters ELASN, PON, and VSLEAK). Under those conditions, the seal types are expected to have dissimilar performance attributes.

A discussion of the quantification of the parameters is presented below. Failure probabilities are provided on a single basis.

8.2.1 RCP Stage Failure due to Elastomer Degradation (ELASN)

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The elastomer degradation failure probability assessment was modified from the analysis performed in WCAP-16175-P-A in order to incorporate longer duration high temperature/high pressure elastomer tests of EP O-rings performed by Westinghouse and, more recently, by KSB into the failure probability model. This also allowed extension of the failure probabilities to 72 hours. In this analysis, elastomer failure probability was quantified by parsing data into seven distinct exposure intervals due to the time dependency of this failure mechanism. These exposure intervals are:

Time Interval 1:	0.1 hr < D ≤ 1 hr
Time Interval 2:	0 hr < D ≤ 2 hrs
Time Interval 3:	0 hr < D ≤ 4 hrs
Time Interval 4:	0 hr < D ≤ 8 hrs
Time Interval 5:	0 hr < D ≤ 18 hrs
Time Interval 6:	0 hr < D ≤ 24 hrs
Time Interval 7:	0 hr < D ≤ 72 hrs

Where D is the duration of exposure to the thermal challenge.

The time intervals were determined based on available plant data or experiments (see the data in Reference 1, Section 8, Table 8-1, and Reference 11, Table 2) and related information provided by KSB (see Section 6). It should be noted that the elastomer data included in the qualified elastomer mix has been extended to include results of high temperature, high pressure Westinghouse O-ring experiments. The following assumptions were made when analyzing the data:

1. All seal stages that survived to the next time interval were not failed in the previous interval. Of all seal observations, only one elastomer failure was identified. This failure was of a Nitrile elastomer. The failure was noted to occur by four (4) hours. This failure was included in the < 8 hour elastomer survival interval. Nitrile material was not considered beyond 8 hours. No failures of qualified EP based material were noted for the duration of the tests under RCS operating conditions.
2. When using operation event data, if CBO was not isolated in < 20 minutes, then all seal stages except for the vapor seal are assumed to experience high temperatures. Therefore, for a 3-stage

seal, 2 stages are affected. This assumption is based on the seal heatup characteristics observed in the BJ/Sulzer seal test data (Reference 1). When CBO is isolated within 20 minutes, then only one stage is assumed to be affected (the lower stage).

BNL, Reference 10, identified the elastomer degradation related RCP seal stage failures as being due to binding and extrusion of the elastomer and are considered unlikely for qualified O-rings. Qualified O-rings are those that have been specifically qualified for high temperature performance (see Section 3.2.2). The EP compounds used in O-rings and other sealant components are considered qualified and consequently can withstand exposure to a high temperature condition for an extended period. Qualified elastomers are exclusively used in the KSB Type F pump seal[19].

The stage elastomer failure probabilities were established from the operating experience data by observing the number of seal stages exposed to a high temperature environment [> 500°F (260°C)], the duration of the exposure, and the number of elastomer degradation related failures occurring for the various exposure durations. As discussed above, it was assumed that the vapor seal elastomers would not see the high temperature conditions; therefore, when using operational event data, the vapor seals were not included in the exposure count. The stage thermal failure probability for each duration was calculated using the standard equation,

$Q(N) = F/N$

Where F is the number of applicable failures, and N is the number of seal stages exposed for a given duration.

In most instances no elastomer failures were observed.

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[19] Nitrile elastomers have been involved in elastomer assessment. This impacts only short duration exposures, as Nitrile is not seen in long duration exposures. This treatment provides additional conservatism on low temperature exposure failure estimates.

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Table 8.2-1: Summary of Typical O-Ring Exposure Observations and Test Data (High Temperature Exposure > 500°F)

Duration of Exposure

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Table 8.2-2: Summary of Typical O-Ring Exposure Observations and Test Data (Including Moderate Exposure Testing (~400°F) Duration of Exposure

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a,c

were assumed to not pose a significant challenge to the RCP seal elastomers for short term exposures.

The following paragraphs define the individual elastomer failure probabilities used in the models.

- **CONDITION 1: CBO NOT ISOLATED**

The KSB HDD-254 Type F seal design uses high quality EP elastomers. The thermal exposure experienced by the lower two stages (given a LOSC without CBO isolation) is approximated by the temperature distribution in Table 4.3-3. The elastomer failure probabilities to be used for basic event entries are taken from mean failure probabilities included in Table 8.2-1 and Table 8.2-2 and are presented in Table 8.2-3. Note that elastomers included in the first two stages are considered subjected to high seal temperatures, while seal failure probabilities for the vapor (third) stage are treated as being exposed to lower temperature environment [ ]^{a,c}.

Table 8.2-3: KSB Type F Elastomer Failure Probability Given CBO Not Isolated

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- **CONDITION 2**: **CBO ISOLATED**

As discussed in Section 4.3.1, if CBO is isolated within about 10 minutes of the LOSC, the temperatures in the lower seal stages will be well below the expected equilibrium temperatures (e.g., in the 250°F (120°C) range in the short term). The temperatures would gradually increase due to conduction but would remain well below 400°F (204°C) for a substantial period of time. Failure probabilities are established based on inclusion of KSB moderate temperature exposure tests (see Table 8.2-4). The elastomer failure probabilities to be used for basic event entries are taken from mean failure probabilities included in Table 8.2-2 (low temperature exposure condition).

For the case where the CBO is isolated, the lower seal stages will, early on, be at or well below the expected equilibrium temperature (based on timing of isolation) of approximately 300°F – 400°F (149°C – 200°C) range, depending on operator action. The temperatures of the lower seals will gradually increase due to conduction. Over time, the vapor stage reaches temperatures of about 400°F (200°C).[20] As a result of low temperature challenge to the RCP seals early in the seal heatup process, the 0.001 seal stage failure probabilities are assigned for all exposures less than 4 hours. [

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The parameter VSLEAK (See Section 8.2.6) is included in the model to account for the potential implications of CBO isolation with an accompanying leak in the third stage seal that is sufficiently large enough to alter the conditions in the upper seal stages. The third stage seal could develop a leak prior to, or immediately after, CBO isolation. Such leakages may result under LOSC conditions with delayed isolation. This leakage term was discussed in RAI 2.7 of Reference 1. [

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Table 8.2-4: KSB Type F Elastomer Failure Probability Given CBO Isolated within 10 Minutes

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	Time Frame					

Table 8.2-5: KSB Type F Elastomer Failure Probability Given CBO Isolated within 20 Minutes

a,c

	Time Frame					

8.2.2 Random Failure Probability (RFN)

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Operational data for the Type C seal relevant to the assessment of seal reliability is presented below for the German and Korean experience:

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a,c

Table 8.2-6 summarizes the resulting random failure probabilities. As discussed above, the random failure probability can be applied to the KSB Type F seals based on similar design and the expectation that overall seal performance and nominal leakage performance under normal conditions is expected to be the same.

Table 8.2-6: KSB Random RCP Seal Stage Failure Probability (RF)

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8.2.3 Hydraulic Instability/Pop-Open and Stage Failure (PON)

Basic event PON considers the potential for a pop-open and subsequent failure of a stage seal. Seal Stages 1 and 3 are treated as independent events due to differences in their operating conditions. A review of past events suggests that Stage 2 has a common cause failure relationship with Stage 3 when CBO is not isolated. In events where Stage 3 failure is observed, Stage 2 is sometimes found to be degraded. That is, failure of Stage 3 will adversely impact failure of Stage 2 under conditions when CBO is not isolated. [ ]^{a,c} This value is assumed constant with temperature, as temperature-induced seal failures are dominated by the elastomer failure basic event.

A pop-open seal stage failure requires the coincidence of three conditions: (1) the elastomer for the stationary seal face follower has thermally degraded such that it will prevent the stationary seal face follower from moving downward to maintain contact with the rotating seal stage face, (2) the RCP shaft and, hence, the rotating seal stage faces are moving downward due to depressurization of the RCS or differential thermal expansion of RCP shaft and seal components, and (3) the thermal-hydraulic conditions in the vicinity of the seal stage faces are amenable to a pop-open due to hydraulic instability. This assessment conservatively looks only at the thermal hydraulic conditions when evaluating the potential for the pop-open. (Note: an intermittent pop-open condition will only cause a temporary loss of stage pressure and will not by itself cause a sustained stage failure.)

[

]^{a,c}

Note that no pop-open behavior was noted in the N-9000 SBO test. Pop-open for these newer designs were established assuming that of the six identified potential pop-open events observed on older designs, three (or one half) of those events would be assumed to be applicable to the newer designs. This is relevant to the KSB seal, as the KSB seal design team does not expect the seal to be prone to this failure mode. Observations on the KSB integral test rig indicates that no pop-open behavior was observed [$]^{a,c}$ during the integral small leakage test program. [

$]^{a,c}$ Assuming the conditional probability of pop-open has a binary failure mode, it is reasonable to represent the pop-open failure mode failure probability with a binomial distribution with a mean probability of "success" (i.e., seal pop-open occurs) as [
$]^{a,c}$

Discussions with KSB seal designers suggest that the KSB Type F seal design is not expected to be prone to pop-open failures. To test this, the KSB seal was subjected to a low subcooling environmental test. Using a prototypical seal, the third stage of the KSB seal was subjected to low subcooling conditions. Test results are discussed in Section 6.2.2.4. [

$]^{a,c}$ Seal operation remained stable. [

$]^{a,c}$ Given the favorable results of the pop-open test, the seal pop open probability is likely lower than the baseline WCAP-16175-P-A value. The pop-open parameter for the KSB Type F design is maintained at [$]^{a,c}$ for Stages 1 and 2 operation under highly subcooled conditions and third stage operation for any subcooling condition. Stable conditions under third stage operation for nearly saturated conditions were confirmed by the KSB test discussed in Section 6.2.2.4. Pop-open failure probability for low subcooling conditions was treated consistently with Reference 1.

Table 8.2-7: RCP Seal Stage Pop-Open Failure Probability Calculation
(Extracted from Reference 1)[21]

a,c

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[21] No events expected, three events assumed.

Details of the RCP seal thermal hydraulic conditions are discussed below. In establishing pop-open probability, four thermal hydraulic conditions are considered representing the fundamental post-LOSC operating conditions. These states reflect the impact of local seal stage temperature, pressure, and subcooling on the hydraulic stability of the various RCP seal stages.

•Condition 1: CBO Isolated and RCS Cold Leg Subcooled

a,c

Table 8.2-8: Stage Pop-Open Failure Probability when RCS is Subcooled and CBO is Isolated

KSB Type F 3-Stage Seal

a,c

- **Condition 2: CBO Isolated and RCS Saturated**

[

]^{a,c}

The KSB seal is designed to be [

]^{a,c}

As discussed above, [

]^{a,c} Test results support the conclusion that the seal stage will remain stable under these conditions; consequently, the lower failure probability of [ ]^{a,c} (representative of a highly unlikely failure probability) is assigned.

Table 8.2-9: Stage Pop-Open Failure Probability when RCS Subcooling < 50°F CBO is Isolated KSB Type F 3-Stage Seals

a,c

- **Condition 3: CBO Not Isolated and RCS Subcooled**

[

]^{a,c} Based on KSB pop-open seal testing for Stage 3, the seal is expected to operate in a stable manner even at very low subcooling. [
]^{a,c}

[
]^{a,c}

Table 8.2-10 presents the pop-open probabilities by stage for the 3-stage seals when RCS is subcooled and CBO is not isolated.

Table 8.2-10: Stage Pop-Open Failure Probability when RCS is Subcooled and CBO is Not Isolated KSB Type F 3-Stage Seals

a,c

- **Condition 4: CBO Not Isolated and RCS Saturated**

In this case, [

]^{a,c}

Table 8.2-11 presents the pop-open probabilities by stage for the 3-stage seal when RCS subcooling < 50^{o}F and CBO is not isolated.

Table 8.2-11: Stage Pop-Open Failure Probability when RCS Subcooling < 50^{o}F and CBO is Not Isolated KSB Type F 3-Stage Seals

a,c

8.2.4 Common Cause Relationships[22],[23]

a,c

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[22] Reference 19

[23] Reference 8

8.2.5 Treatment of Pre-Existing Failure (TMN)[24]

a,c

8.2.6 Vapor Stage Leaks Enough to Restage Seal (VSLEAK)

Isolation of the CBO destages the RCP seal such that the entire pressure drop is across the vapor stage. The lower stages are not subject to pop-open failure because there is no pressure drop across the stage seal faces. If the vapor stage fails, the resultant flow will restage the lower stages. Under these conditions, the lower stages may be subject to the pop-open failure mechanism as discussed in Section 8.2.3.

Another potential mechanism that could restage the lower stages would be if the vapor seal had excess leakage. While this is not sufficient to consider the vapor stage failed, it would change the conditions experienced by the lower stages.[25]

a,c

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[24] From Table 8.2-4, [ ]^{a,c}

[25] Variance = $\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$ α= number of failures and β = number of successes.

9 QUANTIFICATION OF FAULT TREE MODELS FOR THE EVENT TREE THERMAL EXPOSURE TIME TOP EVENT

9.1 EVENT TREE TOP EVENTS AND FAULT TREE MODELS

The RCP seal failure event tree presented in Section 7 is included for information the utility might utilize to generate a full PRA model of KSB Type F RCP seal LOCA events. The event tree has an initiator input and four top events.

The initiating event for entering the RCP seal failure model is any event that leads to a loss of cooling for the RCP seals. These events include SBO or a combined loss of CCW and seal injection to the RCP seals. The specific initiating event frequencies are not included in the scope of this evaluation.

The first top event questioned in the event tree is RCPs secured within 20 minutes. For a LOOP/SBO initiator, the <u>success</u> probability for this branch is defined to be 1.0. Otherwise, this event probability is based on operator actions modeled in the baseline PRA.

The second top event questioned in the event tree establishes whether or when CBO is isolated. The probability that CBO is successfully isolated within 10 minutes or 20 minutes is a function of plant procedures and the specific initiator or in the case of plant’s equipped with the PTCV, the PTCV demand reliability. KSB Type F RCP seal failure data tables for both 10 minute CBO isolation and 20 minute CBO isolation have been provided. The plant selects the CBO isolation time as supported by applicable procedures and human reliability analysis.

The third top event questioned in the event tree is RCS subcooled. The underlying question is whether the operators control the plant to keep the RCS subcooled. This can occur if the plant remains at hot standby or if the plant is cooled down such that the subcooled margin is maintained greater than 50°F (27.8°C). Again, the success probability for this branch is a function of plant emergency and abnormal operating procedures and the initiating event. KSB Type F RCP seal failure data tables for both RCS subcooling >50°F (27.8°C) and <50°F (27.8°C) subcooling have been provided. The plant selects RCS subcooling as supported by applicable procedures and human reliability analysis.

The fourth top event questioned in the event tree is Thermal Exposure Time. This question pertains to the probability that a KSB Type F RCP seal will fail within a specified exposure time given the RCS thermal conditions defined by the responses to the three previous top events. The RCP seal failure fault tree models in Section 7.2 are used to evaluate this top event for six (6) specific time frames: (1) exposure < 1 hour, (2) exposure up to 2 hours, (3) exposure up to 4 hours, (4) exposure up to 8 hours, (5) exposure up to 24 hours, and (6) exposure time < 72 hours. For LOOP initiated events, exposure time is based on the time for offsite power recovery.

The event tree presented in Section 7.1 has a total of 25 end points of interest. These reflect the various combinations of RCS conditions and exposure times. The KSB Type F RCP seal failure fault tree model for the Thermal Exposure Time top event was quantified to provide 24 of these end points using the parameter values derived in Section 8. These KSB Type F seal parameters related failure probability basic events are presented in Table 9.1-1 through Table 9.1-6. Summary end state seal failure probabilities determined using mean parameter values identified in Table 9.1-1 through Table 9.1-6 are summarized in Table 9.1-7.

Table 9.1-1: RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

Table 9.1-2: RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

Table 9.1-3: RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

Table 9.1-4: RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

Table 9.1-5: RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

Table 9.1-6: RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

Table 9.1-7: Summary of Conditional RCP Seal Probabilities for the 3-Stage KSB Seal Design (Type F)

a,c

9.2 COMPARISON OF RESULTS WITH TOPICAL REPORT

The results for the KSB Type F 3 Stage seal design were reviewed against the TR (Reference 1). Table 9.2-1 compares the point estimates for the Sulzer Balanced Stator 3-Stage Seal design from the TR (Reference 1) with the point estimate results for the KSB Type F 3-Stage Seal design for the 24 hour interval.

Table 9.2-1: Comparison of 3-Stage KSB Seal Design (Type F) with Sulzer Balanced Stator 3-Stage Seal Design

a,c

For post-ELAP conditions, KSB Type F RCP model results are lower than the equivalent prediction for the Sulzer balanced seal design.

10 TREATMENT OF MODEL UNCERTAINTIES

The RCP seal model and the associated model parameters are largely developed based on a review of RCP seal separate effects and integral tests and observations of plant responses to a number of loss of cooling events. In developing the model and in assigning values to the basic events, several assumptions with model implications were made. In accordance with requirements of the ASME/ANS-Ra-Sa-2009 (Reference 2), Regulatory Guide RG 1.200, Revision 2 (Reference 17), and NUREG-1855 (Reference 18), the intent of this section is to identify and characterize the significant sources model uncertainties (and associated assumptions) and assess their impact on the PRA model. Sections 10.1 through 10.5 are focused on the characterization of model or epistemic uncertainties. Section 10.6 extends the sensitivity assessment by analyzing the impact of seal failure probability in the presence of a failed seal stage. The investigations included in this section are limited to understanding the impact of modeling assumptions made in the development of the KSB Type F RCP seal failure model parameters on predicted RCP seal failure probability only. This information may be used to support a more global assessment of the RCP model uncertainty on the plant core damage profile.

The KSB Type F RCP seal failure models involve an inter-relationship among the temperature capabilities of the O-rings used in the seal design, the likelihood of a pop-open event given a range of post-accident RCS, and RCP seal conditions and pre-existing seal conditions. These issues are addressed via focused sensitivity studies. Sensitivity calculations specifically focused on the 24 hour RCP seal failure end states. Variance values for the adjusted parameters are based on the KSB RCP model baseline values.

10.1 UNCERTAINTY IN ELASTOMER PERFORMANCE

[

]^{a,c}

To estimate the impact of uncertainties in the seal failure probability, a sensitivity analysis was performed on the ELASN seal elastomer failure parameter. The focus of the sensitivity was to investigate the impact of the elastomer data update. Specifically, this sensitivity study compares the current KSB Type F RCP seal model ELASN parameters to the Reference 1 basic event values for equivalent seal challenge conditions. The baseline ELASN values were doubled as shown in Table 10.1-1 resulting in a study that bound the Reference 1 basic event values. Sensitivity studies specifically focused on the 24 hour RCP seal failure end states. These sensitivity cases were designated as ELAS-1A through ELAS-1D.

Table 10.1-1: Elastomer Performance Sensitivity Study #1 Input Parameters

a,c

[ ]^{a,c} therefore, the elastomer failure likelihood during this time period is very low and probability could be reduced for all seal stages. To assess this impact, the baseline [ ]^{a,c} as shown in Table 10.1-2. These sensitivity cases were designated as ELAS-2A and ELAS-2B.

Table 10.1-2: Elastomer Performance Sensitivity Study #2 Input Parameters

a,c

An additional sensitivity study was performed to represent the results from crediting the long term seal survivability tests included in Appendix 4 of Reference 16. [

]^{a,c} This is a reasonable alternative since all EPDM elastomers tested survived at least [ ]^{a,c} exposure, while the expected maximum exposure duration for ELAP events is less than 168 hours. This change in elastomer failure rates was applied to all post-LOSC exposure conditions. These sensitivity cases were designated as ELAS-3A through ELAS-3D.

Table 10.1-3: Elastomer Performance Sensitivity Study #1 Input Parameters

a,c

10.2 UNCERTAINTY ASSOCIATED WITH POP-OPEN FAILURE PARAMETERIZATION

The pop-open failure mechanism has been identified as a potential failure mechanism for hydrodynamic seals. Under normal circumstances, a liquid film of water lubricates the rotating seal faces so that the rotating surfaces do not contact. The seals are designed such that this water flow is very small [ ]^{a,c} This lubrication will be maintained so long as a continuous liquid film is available. As the subcooling of the liquid in the upstream seal cavity significantly decreases the water, the seal gaps may flash as a result of the downstream pressure. This flashing in the seal gap will unbalance the seal loading and force the seal faces apart. If conditions allow this process to be repeated, the seal will ultimately lose its ability to retain RCS pressure. [

]^{a,c}

As a result of the development of the KSB design, the seal designers do not believe this is a significant failure mode for the Type F seal. This has been confirmed by Type F seal pop-open testing presented in Section 6.2.2.4. The present baseline model includes the Reference 1 treatment of seal pop-open. Based on the observed seal performance at low subcoolings, it is likely that the pop-open challenge will be lower. Two series of sensitivity studies are performed. The first study investigates the impact of [ ]^{a,c} Setting the pop-open parameter to 0.05 reflects the high estimate for a very unlikely occurrence (see for example Reference 25). These sensitivity cases were designated as PO-1A through PO-1D. [

]^{a,c}

Table 10.2-1: Pop-Open Sensitivity Input Parameters

a,c

Table 10.2-2: Pop-Open Sensitivity Input Parameters

a,c

The second series of sensitivity studies focuses on the presumption that the pop-open phenomenon is an extremely unlikely event for the KSB seal because the KSB seal designers expect no significant impact by exposure to low subcooled conditions. In this study the "no challenge" condition remains as is defined in the baseline model, and challenge condition probabilities are reduced [ ]^{a,c} This value is still considered to overstate the pop-open impact, but is considered to represent an extremely unlikely failure (as defined in Reference 25). These sensitivity cases were designated as PO-2A through PO-2D. The sensitivity study parameters were changed as identified in Table 10.2-3 and Table 10.2-4.

Table 10.2-3: Pop-Open Sensitivity Input Parameters

a,c

Table 10.2-4: Pop-Open Sensitivity Input Parameters

a,c

10.3 UNCERTAINTY IN MODELING SEAL STAGE UNAVAILABILITY AND RANDOM FAILURE PROBABILITIES

Unavailability and random failure probabilities are established from information obtained from KSB. This information included reported stage failures as well as other operational issues from KSB German clients. The resulting random failure (RF) and unavailability parameter (TM) were reduced. As stage failure information is not required by regulation to be maintained or transmitted to KSB, it is possible that the data set used in the evaluation is incomplete and failures may be under-reported. [

]^{a,c} The resulting RF and TM parameters used in the sensitivity study are presented in Table 10.3-1. These changes are applied to all seal exposure conditions. This sensitivity case is designated as RF-1.

Table 10.3-1: Unavailability/Random Failure Sensitivity Study Input Parameters

a,c

10.4 COMBINED IMPACT OF UNCERTAINTIES

a,c

10.5 RESULTS OF UNCERTAINTY ASSESSMENT

A complete set of results of the uncertainty assessment and sensitivity studies identified in Sections 10.1 through 10.3 are tabulated in Table 10.5-1 for the 24 hour RCP seal failure end states. The analyses were performed using CAFTA to generate point estimates that were used for comparison purposes with the appropriate baseline cases.

The sensitivity studies presented in Table 10.5-1 and designated with the A or B suffix focus on the RCP seal failure probabilities following a LOSC for the condition where the CBO is isolated quickly after a LOSC event. The sensitivity studies presented in Table 10.5-1 and designated with the C or D suffix focus on the RCP seal failure probabilities following a LOSC for the condition where the CBO is not isolated after a LOSC event. These studies specifically investigate the impact of varying mean failure probabilities for the various RCP seal failure mechanisms separately (as described in Sections 10.1 through 10.3) and in combination (as discussed in Section 10.4).

a,c

Table 10.5-1: Summary of Sensitivity Study for RCP Seal Failure Following Loss of Seal Cooling

a,c

10.6 PRE-EXISTING STAGE FAILURE

a,c

Table 10.6-1: Impact of Pre-Existing RCP Seal Failure on RCP Seal Failure Probability Following Loss of Seal Cooling

a,c

11 COMPARISION TO ASME/ANS-RA-Sa-2009

This section summarizes the relationships between the RCP seal model and the ASME/ANS RA-Sa-2009 version of the PRA standard. That standard version of the PRA standard is endorsed by the U.S. NRC through RG 1.200, Revision 2. Note that the PRA standard is intended to be applied to a plant level PRA. The relevant elements of that standard have been selected for a focused comparison to the specific PRA elements associated with the RCP seal failure model. This assessment confirms that the relevant elements of the PRA RCP seal model satisfy the relevant requirements such that it may be used to develop a Category II PRA.

The ASME/ANS PRA Standard is intended to be used to evaluate complete PRAs. However, by using key supporting requirements as a benchmark, a number of supporting requirements can be identified which contribute to an improved model. To determine the scope of this review, the standard high level requirements (HLRs) and supporting requirements were reviewed and selected for a focused risk evaluation. Table 11-1 identifies HLRs applicable to the RCP seal model along with the relevant supporting requirements and a roadmap identifying within the document where the relevant supporting requirements are addressed.

The focus of this review is to address the RCP seal model structure and quantification process only.

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

Table 11-1: Comparison of RCP Seal Model Properties to Related ASME/ANS PRA Standard Supporting Requirements (cont.)

a,c

12 IMPLEMENTATION GUIDANCE

This report provides the technical basis and PRA models for use in integrating a realistic RCP seal failure model into a plant level PRA. High level guidance for performing this integration is provided below.

The RCP seal failure model defined in this report includes LOSC response bin end states. These end states are divided into success and failure categories based on CBO isolation timing and RCS subcooling. Each of these categories contains seven sub-categories based on thermal exposure duration for the event. Table 9.1-7 provides mean probabilities (and variances) for each end state. Implementation of the seal failure within the structure of plant-specific PRA requires that the PRA identify those events that represent the LOSC and establish the potential event strategies being used. This activity requires the PRA analyst to integrate the Figure 7-1 event tree end states into the PRA. This may be done as follows:

a,c

Common cause failure factors for multiple RCP seal failures given the failure of one RCP seal are applied to the plant level model to address multiple RCP seal failures.

Interface parameters and basic events need to quantify the Section 7 event tree, such as quantification of human error probabilities for isolating CBO or shutting down the RCPs given a LOSC event are outside the scope of this present effort.

13 SUMMARY & CONCLUSIONS

This technical report provides an extension to Reference 1 by developing a KSB seal-specific RCP seal PRA model for establishing the probability of RCP seal failure following a LOSC. The RCP seal failure model described in the report is applicable to the new generation KSB HDD-254 Type F seal package. Model enhancements include consideration of KSB-specific RCP seal separate effects and integral system tests performed at KSB, as well as past operating experience of the KSB RCP seals. Seal failure probabilities for LOSC scenarios are summarized in Table 9.1-7 of this report.

Results of the analysis indicate that the KSB HDD-254 Type F seals have conditional failure probabilities for a 24 hour duration LOSC event range from [ ]^{a,c} depending on the status of CBO isolation. These failure rates are approximately [ ]^{a,c} lower than those associated with the 3-stage package seal evaluated in Reference 1 (see Table 9.2-1). Thus, the Type F seal is predicted to have robust capability to accommodate LOSC events.

Seal failure probabilities for degraded operation (one stage inoperable) are also provided for use in off-design operational assessments (see Section 10). RCP operation in the presence of a degraded/failed seal stage significantly increases the LOSC conditional failure probability, suggesting that extended operation with failed seals can impact the plant risk profile.

14 REFERENCES

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APPENDIX A: ASSESSMENT OF KSB HDD-254 RCP SEAL MODEL WITH WCAP-16175-P-A SAFETY EVALUATION

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

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Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

a,c

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

a,c

U.S. NRC Condition/Limitation	Status

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

a,c

U.S. NRC Condition/Limitation	Status

a,c

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

U.S. NRC Condition/Limitation	Status

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

a,c

U.S. NRC Condition/Limitation	Status
	.

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

a,c

U.S. NRC Condition/Limitation	Status

Table A-1: Assessment of KSB Type F RCP Seal Model/Information to U.S. NRC Conditions and Limitations

a,c

U.S. NRC Condition/Limitation	Status