CEOG COMBUSTION ENGINEERING OWNERS GROUP

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Model

for

Failure of RCP Seals Given Loss of Seal Cooling

CEOG Task 1136

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C E Nuclear Power LLC

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

TABLE OF CONTENTS (cont'd)

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (cont'd)

ACRONYMS

Acronym	Definition
AAC	Alternate AC power
ABB	Asea Brown Boveri
ACRS	Advisory Committee on Reactor Safeguards
AECL	Atomic Energy of Canada Limited
AHAC	Advisory Ad Hoc Committee
ANO	Arkansas Nuclear One
ANS	American Nuclear Society
AOV	Air operated valve
ANSI	American National Standards Institute
APS	Arizona Public Service
ASLE	American Society of Lubrication Engineers
ASME	American Society of Mechanical Engineers
BG&E	Baltimore Gas & Electric
B&W	Babcock & Wilcox
BJ	Byron Jackson (now Flowserve: formerly BW/IP)
BNL	Brookhaven National Laboratory
BWC	Bingham Willamette Co. (now Sulzer Pumps)
BWR	Boiling water reactor
CBO	Controlled bleed-off
CCW	Component cooling water
CDF	Core damage frequency
CE	Combustion Engineering
CEOG	Combustion Engineering Owners Group
CFR	Code of Federal Regulations
CMF	Core melt frequency
CRGR	Committee to Review Generic Requirements (NRC)
CVCS	Chemical & Volume Control System
DBA	Design Basis Accident
EAC	Emergency AC power
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generator
EP	Ethylene Propylene
EPDM	Ethylene Propylene Diene Monomer
EPRI	Electrical Power Research Institute
ESFAS	Engineered Safeguards Features Actuation Signal
ESW	Essential Service Water, or extremely severe weather
ETEC	Energy Technology Engineering Center
FAI	Fail-as-is
FC	Fail closed

ACRONYMS (Cont'd)

Acronym	Definition
FO	Fail open
FP&L	Florida Power & Light
FR	Federal Register
GDC	General Design Criteria (10 CFR Part 50, App A)
GI	Generic Issue (NRC)
GL	Generic Letter (NRC)
GPH	Gallons per hour
GPM	Gallons per minute
GTG	Gas Turbine Generator
HPI	High Pressure Injection
INPO	Institute of Nuclear Power Operations
IPE	Individual Plant Examination
KSB	Klein, Schanzlin & Becker
LCO	Limiting Condition of Operation
LER	Licensee Event Report
LOAC	Loss of AC power
LOCA	Loss of Coolant Accident
LO	Locked-open
LOCCW	Loss of Component Cooling Water
LOOP	Loss of Offsite Power
LOSC	Loss of Seal Cooling
LOSW	Loss of Service Water
LWR	Light Water Reactor
MGL	Multiple Greek Letter
MOV	Motor-operated valve
MP2	Millstone Point Unit 2
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
NPRDS	Nuclear Plant Reliability Data System
NPSD	ABB CE Nuclear Power Systems Document
NSSS	Nuclear Steam Supply System
NU	Northeast Utilities
NUMARC	Nuclear Utility Management and Resource Council
OPPD	Omaha Public Power District
PBD	Pressure Breakdown Device
PCV	Pressure Control Valve
PO	Pop-Open
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Analysis

ACRONYMS (Cont'd)

Acronym	Definition
PSIA	Pounds per square inch, absolute pressure
PSIG	Pounds per square inch, gage pressure
PSIP	Pump Seal Improvement Program
PVNGS	Palo Verde Nuclear Generating Station
PWR	Pressurized Water Reactor
QA	Quality Assurance
RAB	Reactor Auxiliary Building
RAI	Request for Additional Information
RBCCW	Reactor Building Component Cooling Water
RCDT	Reactor Coolant Drain Tank
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR	Residual Heat Removal
SBO	Station Blackout
SCE	Southern California Edison
SCHx	Seal Cooling Heat Exchanger
SIAS	Safety Injection Actuation Signal
SIS	Safety Injection System
SOER	Significant Operating Event Report (INPO)
SONGS	San Onofre Nuclear Generating Station
STLE	Society of Tribologists and Lubrication Engineers
SW	Service Water
SWR	Severe Weather Recovery
TS	Technical Specifications
VCT	Volume Control Tank
W	Westinghouse
WSES3	Waterford Steam Electric Station Unit 3

1.0 INTRODUCTION

1.1 Purpose

The purpose of the work presented herein is to develop and present a mechanistic methodology for estimating the probability of failure of an RCP seal given loss of cooling to the seal. This model is intended for use in the individual CE plants' PSAs to quantify the risk of an RCP seal LOCA given the occurrence of a Loss of Seal Cooling (LOSC) event.

1.2 Scope

CE plants have never experienced a RCP seal failure. There have been RCP seal stage failures during normal operation but no seal failures. There have also been operational events in which seal cooling was lost to one or more RCP seals. A few of the operational events resulted in the failure of a single stage, but again, there were no RCP seal failures. However, in the past, the NRC has not accepted this operating experience as providing conclusive evidence of the robustness of the RCP seals used by CE plants.

CEOG interest in modeling RCP seal failures was initiated in 1992. This initial effort was later extended in 1996 with the issuance of CE NPSD-755, Rev. 01, "Reactor Coolant Pump Seal Failure Probability Given a Loss of Seal Injection"[1].CE NPSD-755, Rev. 01 presented a Multiple Greek Letter (MGL) model for determining the probability of a RCP seal failure given a loss of seal cooling and seal injection for a RCP seal of the type used by CE plants.

Given renewed interest in the RCP seal failure models used in plant PSAs, especially for CE plants, the Combustion Engineering Owners Group authorized a project to develop a mechanistic CEOG RCP Seal Failure model for loss of seal cooling conditions. The results of this effort are the subject of this report. This model:

(1) incorporates a technical description of the seals used in CE plants,
(2) incorporates a technical discussion of the failure mechanisms of concern,
(3) evaluates the impact of influencing factors such as controlled bleed-off status and RCP operating status on the seal failure probability,
(4) develops and quantifies a mechanistic seal failure model, and
(5) defines the expected leakage rates for various combinations of seal stage failures.

The mechanistic RCP seal failure model is quantified using a combination of operating experience data, the results from past RCP seal tests, any available analytic models and expert opinion. This approach is consistent with the approach outlined by Brookhaven National Laboratories (BNL) in the "Guidance Document for Modeling of RCP Seal Failures"[2]. The scope of this project did not include the performance of any additional tests nor did it include the development of any new analytic models to evaluate the physical response of the RCP seals.

1.3 Background

In November 1982, the NRC assigned a high priority to the investigation of RCP seal failures, and in October 1983, established Generic Issue 23[3] (GI-23), *Reactor Coolant Pump Seal Failure,* for resolution of this issue. These actions were taken on the basis of operation data, which, at the time, indicated a high likelihood of seal failure if the seals were not properly operated and maintained. The main concern was that leakage of reactor coolant could occur at levels exceeding the capacity of the make-up systems and thus result in a Loss of Coolant Accident (LOCA). The staff's studies at the time indicated that loss of seal cooling was the most likely mechanism by which an otherwise properly maintained seal might lose integrity by "popping open". The staff interacted extensively with the industry on this issue. The attention paid to RCP seals by the industry and the NRC resulted in improved seal performance during normal operation. However, the NRC remained concerned about possible effects of seal failure during a range of off-normal conditions such as Station Blackout (SBO), loss of essential service water, and loss of component cooling water.

In April, 1991, the NRC staff published a Federal Register Notice[4] soliciting comments on the understandings, findings and potential recommendations regarding GI-23 along with a draft Regulatory Guide, DG-1008[5]. In August 1994, the NRC staff issued SECY-94-225[6], a proposed rulemaking package on GI-23. On March 31, 1995, the Nuclear Regulatory Commission issued its Staff Requirements Memo (SRM) disapproving the proposed rulemaking package on GI-23 that had been requested in SECY-95-225. The commission disapproved the proposed rulemaking, stating there were "insufficient basis for gains in safety and there may be some concerns with seal evaluation models. There is also a wide range of plant-specific considerations for PWRs, some of which would result in expending significant resources without a commensurate benefit."

In early 1999, the NRC announced that they planned to take action in the next few months to close Generic Safety Issue 23. The NRC noted that the generic issues program had been revised. Under the new process "closure" of an issue means it is closed and no further action is needed. In the new process "resolved" means that sufficient information is available to assign the issue a low priority for "closure". The NRC noted that they would be using "risk-informed" decision making in the revised generic issues program.

The NRC approach to GI-23 is to "resolve" the issue. The NRC feels the issue is not generic and should be handled on a plant specific basis by reviewing the plant PSA and the importance of RCP seal failure to individual plant risk. To this end the NRC would like plant specific information on operations procedures and action taken during station blackout and loss of cooling to the seals. The NRC was especially interested in PSA risk assumptions and the "pop-open" failure mode for the RCP seals.

2.0 EXPLANATION OF TERMINOLOGY

The following explanations are provided, in alphabetic order, to ensure consistent understanding of terms used in this report.

Balance Diameter:

Seal sizes are given in inches in terms of "balance diameter", which is neither the OD nor the ID of the seal face, but rather is a calculated value and physically is typically the secondary seal sleeve diameter. In the case of the BJ SU seal, it is the shaft sleeve outside diameter under the U-cup. In the case of the 9 inch N-9000 seal it is the balance sleeve outside diameter under the Quad-ring. In the case of the Sulzer seal it is secondary seal sleeve outside diameter under the O-ring.

Balance Ratio:

Area Balance ratio is the ratio between the area exposed to hydraulic forces acting to close the seals to the contact area between the seal faces. Hydraulic balance is the ratio of closing forces to opening forces based on an assumed pressure gradient between the faces. . In "balanced" seals, The hydraulic force acting to close the seals has been designed to be less than 100%. The balance ratio is typically 70% of the corresponding pressure across the seal face. Balancing is commonly accomplished by a step in the shaft to reduce the hydraulic area.

Controlled Bleedoff:

All seal designs use a pressure breakdown system and controlled leakage called Controlled Bleedoff (CBO). CBO is that RCP leakage flow that is intentionally leaked through the seal cartridge in order to provide lubrication and cooling for the moving seal parts. The CBO flow varies among CEOG PWRs and typically is designed to be in the range of 0.5 - 3.2 gpm among the plants. If the CBO flow increases, that is an indication that one or more seal stages are not functioning as designed. Sometimes this is a temporary event or a malfunction in the flowmeter and the associated readout equipment. A higher CBO flow rate would be accompanied by a change in seal staging pressures. A decreased CBO flow rate indicates some sort of blockage in one or more of the pressure breakdown tubes. Table 3.2-1 lists the CBO parameters for CE plants.

Excess Flow Check Valve:

A check valve installed in a RCP's CBO line to automatically stop CBO flow if this flow increases to between 10 - 15 gpm. All CE plants except Palo Verde have an excess flow check valve installed in the controlled bleedoff line from each RCP. These check valves are located upstream of the CBO isolation valves and the CBO pressure relief valves. Palo Verde has an orifice in the seal housing to control CBO pressure and to minimize seal leakage to the Volume Control Tank (VCT).

External Seal Leakage:

Leakage from the vapor seal to the ambient containment. Normally a minute and almost undetectable (evaporation) leakage is inherent. If the vapor seal begins to malfunction, such leakage may increase substantially. Up to a certain value of leakage, the fluid will be piped to the reactor drain tank or other suitable destination (depending on plant design). If the leakage rate exceeds the capability of the drainage system, the excess fluid will overflow the top of the seal cartridge and into containment.

Gross Seal Failure:

Seal cartridge behavior resulting in external shaft seal leakage to the containment at a rate sufficient to eventually lead to core uncovery. This is a loss of the integrity of the primary system pressure boundary.

Isolation of Controlled Bleedoff Flow:

The intentional stoppage of CBO flow in the event of loss of seal cooling to reduce the rate of temperature rise in the seal cartridge. CBO flow must never be stopped if the pump is running. This isolation of the flow involves the closure of two valves: the CBO isolation valve and the isolation valve for the CBO relief valve.

Loss of Controlled Bleedoff:

Significant reduction or complete loss of controlled bleedoff flow (most likely in a single pump) caused by the partial or complete blockage of one of the pressure breakdown devices which are arranged in series in the seal cartridge. A failure of the excess flow check valve could be a cause. Loss of CBO could also be caused by inadvertent closure of the CBO isolation valve and the isolation valve for the CBO relief valve. This is a highly unlikely event, but this scenario would involve all 4 pumps since the CBO lines are manifolded downstream of the excess flow check valves.

Loss of Seal Cooling (pumps without seal injection):

Stoppage of cooling water flow to the RCP. The causes could include failure of the cooling water pump, containment isolation, inadvertent actuation of valves in the cooling water system, rupture of a cooling water supply pipe, etc. It must be kept in mind that loss of cooling also involves the RCP motor where the thrust and guide bearings also depend on the cooling water for their proper operation.

Loss of Seal Cooling (pumps with seal injection):

Stoppage of both seal injection AND cooling water flow to the RCP. The simultaneous loss of both cooling sources would usually involve the loss of offsite power. It must be kept in mind that loss of cooling also involves the pump bearing assembly and the RCP motor where the thrust and guide bearings also depend on the cooling water for their proper operation.

Nominal Seal Failure:

Seal cartridge behavior, which requires immediate pump shutdown and seal cartridge replacement. This could mean the loss of two stages in a three-stage seal cartridge, or the loss of three stages in a four-stage seal cartridge. Nominal seal failure could also involve the malfunction of the vapor seal resulting in external leakage ranging from relatively small leakage which is spilling over the top of the cartridge up to, but not including, leakage from gross seal failure.

Seal Degradation:

Seal cartridge operating behavior which deviates significantly from "normal" parameters as defined by the seal manufacturer, and which could eventually require seal cartridge replacement to preclude seal failure, for example, the loss of a seal stage (i.e., the seal stage does not take its proportional pressure drop, or a significant part thereof). The loss of two seal stages in a four-stage seal cartridge requires commencement of an orderly plant shutdown to replace the seal cartridge. Counting every seal degradation as a seal failure is an erroneous approach, which only bolsters the volume of statistical data to incorrectly conclude that there is a problem.

Seal Failure:

See "Nominal Seal Failure" and "Gross Seal Failure".

Seal Face Convergence:

Very early seal development tests led to studies of the inter-relationship between the shape of the gap between the faces, leak rate and the hydraulic balance of flat-faced seals. Analysis showed that when liquid leaks between faces forming a converging gap, the seals are stable with well-balanced full-film lubrication (See Figure 2-1). When the seals formed a diverging gap in the direction of the leakage, the behavior became unstable resulting in physical contact between the faces, which leads to accelerated wear and the generation of heat. The presence of this fluid film at the interface between the rotating and the stationary face means that there will always be some leakage. While this leakage may be so small as to be visually undetectable (it may evaporate when coming out of the vapor seal), it is impossible to eliminate. The objective in seal design, then, is to obtain:

- A stable fluid film between the faces.
- A liquid film which is thick enough to prevent mechanical contact
- A film thin enough to preclude excessive leakage.

In the case of a converging gap, if there is a sudden increase in film thickness due to an external transient, the amount of convergence will decrease and the opening force will also decrease. The imbalance between the closing and opening forces will return the floating face to its original position. Similarly, a sudden transient decrease in film thickness will increase the opening force, again returning the floating face to its original position.

Seal Leakage:

Normally a minute amount of leakage between the mating seal faces, internal to the seal cartridge. This leakage is in addition to the Controlled Bleedoff (CBO) flow, but in comparison to CBO, it is very small. Such leakage is inherent and necessary for the proper functioning of the seals at the interface between the rotating and the stationary faces. This leakage is necessary to establish an ultra-thin film of fluid between the faces to prevent hard contact between the faces, and to provide lubrication and cooling. In the case of degraded seals, this leakage could become large. However, unless there is a multi-stage degradation, the leakage through one seal stage will be limited by the preceding and the following seal stages.

Venting:

The BJ SU seal cartridge must be very carefully vented in the proper sequence as prescribed in the BJ technical manual. The BJ N-9000 and the Sulzer seals are self-venting.

3.0 TECHNICAL DESCRIPTIONS OF CE PLANT RCP SEAL CARTRIDGES

This section provides an overview discussion of the RCP seal operation for CE PWRs and summarizes key RCP seal features and parameters and associated variations of these parameters among the CE designed PWRs.

3.1 Background

CE plants utilize two basic types of seal designs. The early CE PWRs (prior to System 80) employ RCPs designed by Byron-Jackson (BJ) and incorporate 4-stage SU type shaft seal cartridges. Cooling to the seal cartridge was accomplished via the Component Cooling Water (CCW) system. CE System 80 plants (PVNGS Units 1, 2 and 3) employ CE-KSB pumps with 3-stage seals made by KSB in Germany. These designs utilized seal cooling via seal injection and the CCWS*.

The original seal designs did not explicitly consider station blackout and loss of seal cooling conditions in the seal design stage., The pump manufacturers developed more robust seals as operating experience was gained, harsh operating environments were better understood, and analysis technology improved. These newer seals were specifically designed to cope with station blackout scenarios. The improved BJ seal was marketed as the N-9000 design; Sulzer (Bingham) also offered an improved three and four stage seal. A comparison of the BJ SU seals with the newer generation BJ N-9000 and Sulzer seals is presented in Table 3.1-1. It should be noted that the seal improvements included use of high temperature resistant elastomers throughout the seal, and an improved seal face design including thermally superior materials to increase seal hydrostatic stability and predictability during events leading to high temperature exposure. Tungsten carbide has superior thermal conductivity and heat capacity compared to earlier "hard" face materials. This results in markedly reduced susceptibility to thermally induced surface damage (e.g. heat checking) under reduced cooling operation.

Over a period of about 15 years, each utility evaluated its experience with the original RCP seals and made a decision as to whether to continue using the original seals or to change over to another seal type. The present (2000) seal arrangements used in CE nuclear plants located in the USA are summarized in Table 3.1-2. A detailed description of these various seal designs can be found in Appendix A.

* PVNGS seal cooling is provided via the Nuclear Cooling System (NCS).

Table 3.1-1 Comparison Of BJ, SU And N-9000 Designs			
Comment	**BJ SU**	**BJ N-9000**	**Sulzer**
Rotating Face	Titanium Carbide	Tungsten-Carbide	Tungsten-Carbide
Stationary Face	Carbon – Graphite (Resin Impregnated)	Carbon Graphite (Resin impregnated)	Carbon Graphite (Resin impregnated)
Elastomers	Nitril U-cups EP O-rings	Ethylene-Propylene (EP) Only	(EP) Only
Seal type	Balanced Rotor	Stationary Balance	Balanced Stator®

Table 3.1-2 RCP Seal Types in Use at CE Plants		
Seal Type[b, c]	**Plants**	**Approximate Date Of Installation**
BJ SU Seals (4 Stage)	Fort Calhoun	1972
BJ N-9000 Seals (4 Stage)	Arkansas 2	1998, Changed from BJ SU seals
BJ N-9000 Seals (4 Stage)	Millstone 2	RCP A - 1989, RCP B – 1995, RCP C – 1998, RCP D – 2000, Changed from BJ SU seals
BJ N-9000 Seals (4 Stage)	Palisades:	9/1999, Pumps A, C & D Changed from BJ SU seals 2/2000, Pump B Changed from BJ SU seal
BJ N-9000 Seals (4 Stage)	St. Lucie 1	9/1998, Changed from BJ SU seals
BJ N-9000 Seals (4 Stage)	St Lucie 2	9/1999, Changed from BJ SU seals
BJ N-9000/BJ SU-Vapor Stage	Waterford 3[a]	4/1991, Changed from BJ SU seals
Sulzer Seals (4 Stage)	Calvert Cliffs 1 & 2	1989, Changed from BJ SU seals
Sulzer Seals (4 Stage)	San Onofre 2 & 3	1986, Changed from BJ SU seals
Sulzer Seals (3 Stage)	Palo Verde 1, 2 & 3	10/96 (U1), 5/96 (U2), 10/98 (U3), Changed from KSB seals

Notes:

a) Waterford 3 uses N-9000 seals with a BJ SU-type vapor seal stage.
b) Byron Jackson pumps were supplied by the Byron Jackson Pump Company, a Division of Borg Warner, which became BW/IP. Now it is Flowserve.
c) The original name of the company which supplies Sulzer pumps was Bingham Willamette, then became Bingham International, then Sulzer Bingham. Now it is Sulzer Pumps.

3.2 Principles of RCP Seal Operation

Reactor coolant pumps use primary and secondary mechanical seals to limit the leakage of reactor coolant. All CE plant RCP seal designs require that a small amount of leakage be permitted to pass through the seals in order to provide cooling and lubrication between the stationary and rotating parts of the seal. Were it not for this leakage which allows the seal faces to ride on an extremely thin film of fluid, the rotating parts would be in hard contact with the mating stationary parts. A large amount of heat would be generated and the severe wear would result in rapid degradation of the seals.

Although RCP seals exhibit differences in configuration, the general function design of the seals is similar. In these designs, RCS leakage is cooled upon entry to the seal cartridge via use of heat exchangers. The heat exchanger coolant is typically provided from the CCW system or equivalent system. In the case of PVNGS, seal cooling water may also be provided via a seal injection system. Seal cooling is necessary to ensure long life of the elastomers and associated seal components.

The controlled seal leakage serves two purposes: (1) to provide lubrication to the moving parts within the RCP seal cartridge and (2) to establish a pressure breakdown to limit the pressure loss across any single seal stage during normal operation. Typically seals operate at a temperature of less than 150 °F. High temperature seal operation is identified by various seal alarms. In all designs, the primary seals limit the amount of leakage across the seals to values of approximately 1 gal/hour. Controlled bleed-off flows are established based on the design of the pressure breakdown / seal staging devices. Typical operational leakage parameters and component temperature alarms are summarized in Table 3.2-1. Sections 3.2 and 3.3 describe the seal design and operation for a typical 4-stage and 3-stage RCP seal.

Table 3.2-1
CBO Parameters for CE Plants

Plant	Pump RPM	Design CBO Flow (gpm)	Low/High Alarm Setpoint (gpm)	High Temperature Alarm Setpoint
Arkansas 2	900	1.0	0.8/1.1	180 °F
Calvert Cliffs 1 & 2	900	1.5	1.1/2.0	195 °F
Ft. Calhoun	1200	1.0	0.75/1.25	180 °F
Millstone 2	900	1.0	0.75/2.0	180 °F
Palisades	900	1.0	0.75/1.25	180 °F
Palo Verde 1, 2 & 3	1200	3.0	1.6/6.0	175 °F
San Onofre 2 & 3	1200	1.5	1.0 /2.25	195 °F
St. Lucie 1 & 2	900	1.0	0.75/1.25	180 °F
Waterford 3	1200	1.5	1.2/1.8	190.5 °F

3.2.1 RCP Seal Operation: 4-Stage Seal Design

This section presents the key features of the 4 stage RCP seal designs employed in the majority of CE PWRs. The specific design features vary somewhat between the various seal vendors; however, the RCP seal operating characteristics are similar.

During normal plant operation a small amount of coolant from the RCS flows upward along the RCP shaft to the RCP seal cartridge. The temperature of the coolant entering the RCP seal cartridge is controlled via use of a thermal barrier which pre-cools the primary water which passes through the annulus between the pump shaft and the cover on its way to the seals. The controlled clearances within the region of the thermal barrier also serves as a flow restriction in the event of a major seal failure. Prior to entering the RCP seal cartridge, the RCS coolant is further cooled via a seal cooling heat exchanger. The specific design of this heat exchanger varies among seal vendors and designs. A schematic of the four-stage RCP seal assembly is illustrated in Figure 3.2.1-1. The RCP seal assembly contains a Seal Cooling Heat Exchanger (SCHx) and a seal cartridge. The SCHx cools the RCP seal leakage. The stage seal arrangement provides a means of establishing controlled lubrication of the RCP shaft with RCS internal coolant.

For proper functioning the seal cartridge passes a small amount of primary fluid as Controlled Bleedoff (CBO). During normal operation, CBO water (at about 550 °F) enters the seal area through the annulus between the shaft and the cover at a rate of between 0.6 to 1.5 gpm (see for example Table 3.2-1). Prior to entry into the seal cartridge the CBO flow is directed into the seal cooling heat exchanger where the temperature of the CBO water is reduced to ≤ 150 °F.

The CE RCP seals are based on an injectionless, hydrodynamic seal design. In this design the hydrodynamic force generated by the pressure gradient across the seal gap acts to balance the closing forces provided by a hydraulic forces and spring loads. A typical CE RCP shaft seal assembly consists of four mechanical seal stages. Each seal face has one stationary and one rotating face; each stage includes polymer O-rings to seal static gaps, a polymer secondary seal to accommodate small relative motion between parts in the assembly, and a small gap hydraulic primary seal. Each stage operates by maintaining a very small leakage path between the two seal rings which form the primary seal – one mounted on the shaft and the other on the pump housing. That gap is maintained by a balance of forces that can be influenced by the fluid conditions in the seal cavity. Seal cooling and lubrication is established by pumping the primary coolant through a seal heat exchanger cooled by the CCW System. A very thin film of primary fluid maintains cooling and lubrication between the rotating and stationary faces. The remainder of the RCP seal controlled bleedoff passes through the three Pressure Breakdown Devices (PBDs) (one in parallel with each set of the first three seal faces). The PBDs consist of coiled tubes that offer resistance to fluid flow. These PBDs are equistaged such that each seal will take a proportionate part of the system pressure, with each of the first three seals taking approximately one third of the system pressure. The fourth (or vapor seal) operates at a low pressure (about 25-100 psig). Any leakage past the vapor seal cavity passes through a gravity drain line to the reactor drain system. All RCP seal stages are designed to seal at 2500 psig with the pump stationary.

The extent of external seal cooling is dependent on pump design. Experience indicates that seals for most early CE designs utilizing BJ pumps are likely to experience significant heat losses in one or both of the upper two stages (upper stage and vapor stage). This is a result of the design of the seal in relation to the "box" in which it is attached to the pump, in which the upper portions of the pump seal are exposed to the containment atmosphere. Later RCP designs (3410 Mwt plant designs) result in the lower three stages being relatively well insulated. The vapor stage is subject to ambient heat loss to containment. The impact of this heat loss arrangement is significant during various RCP seal accident scenarios.

3.2.2 RCP Seal Operation: 3-Stage Seal Design

Palo Verde Units 1, 2 and 3 were initially designed with CE-KSB reactor coolant pumps and are the only CE PWRs that utilize a three-stage seal design. While the seal dynamics are generally similar to that of the four-stage unit, the three stage RCP seal has several unique features. First, the RCP seal for the Palo Verde units has two sources of seal cooling; a recirculation impeller circulates primary coolant into a heat exchanger cooled by the CCWS and a direct RCP seal injection. In the latter method, cool water from the VCT is directly injected into the seal heat exchanger. These diverse cooling mechanisms significantly decrease the potential for a total loss of seal cooling not caused by a station blackout.

A second unique feature of the Palo Verde three-stage seal is the design of the seal staging. These seals are designed such that the pressure drop across the three stages (two lower stages and the vapor seal) is in the ratio of 0.43: 0:43: 0.14. The pressure drop across the first two stages is controlled via PBDs. The last stage pressure drop is controlled via an orifice. Also as noted in the schematic, cooling coils are externally mounted to maximize natural heat removal following accidents. A schematic of the 3-stage RCP seal is presented in Figure 3.2.2-1.

The KSB seals initially used in the PVNGS units have been replaced by a more robust Sulzer 3 stage design.

3.3 Comments on CBO and Bleedoff Control

RCS leakage is controlled via the controlled bleedoff piping. CBO flow exiting the seal cartridge is subsequently piped into the Volume Control Tank (VCT) and then returned to the RCS via the charging system. Figure 3.3-1 shows a typical CBO line arrangement for CE plants. The CBO line from each RCP includes an excess flow check valve, which is designed to close if the CBO flow from a given RCP reaches 10-15 gpm. This is to prevent overfilling and overpressurizing the VCT should all seal stages on one RCP fail. The check valve contains a valve plug on a spring; if flow in excess of the set flow occurs, the hydraulic drag on the plug overcomes the extension spring force and shuts the valve. This valve does not reopen until the upstream pressure is relieved. The PVNGS design does not use excess flow check valves. Instead, there is an orifice in the seal housing to control the CBO pressure and minimize seal leakage to the VCT.

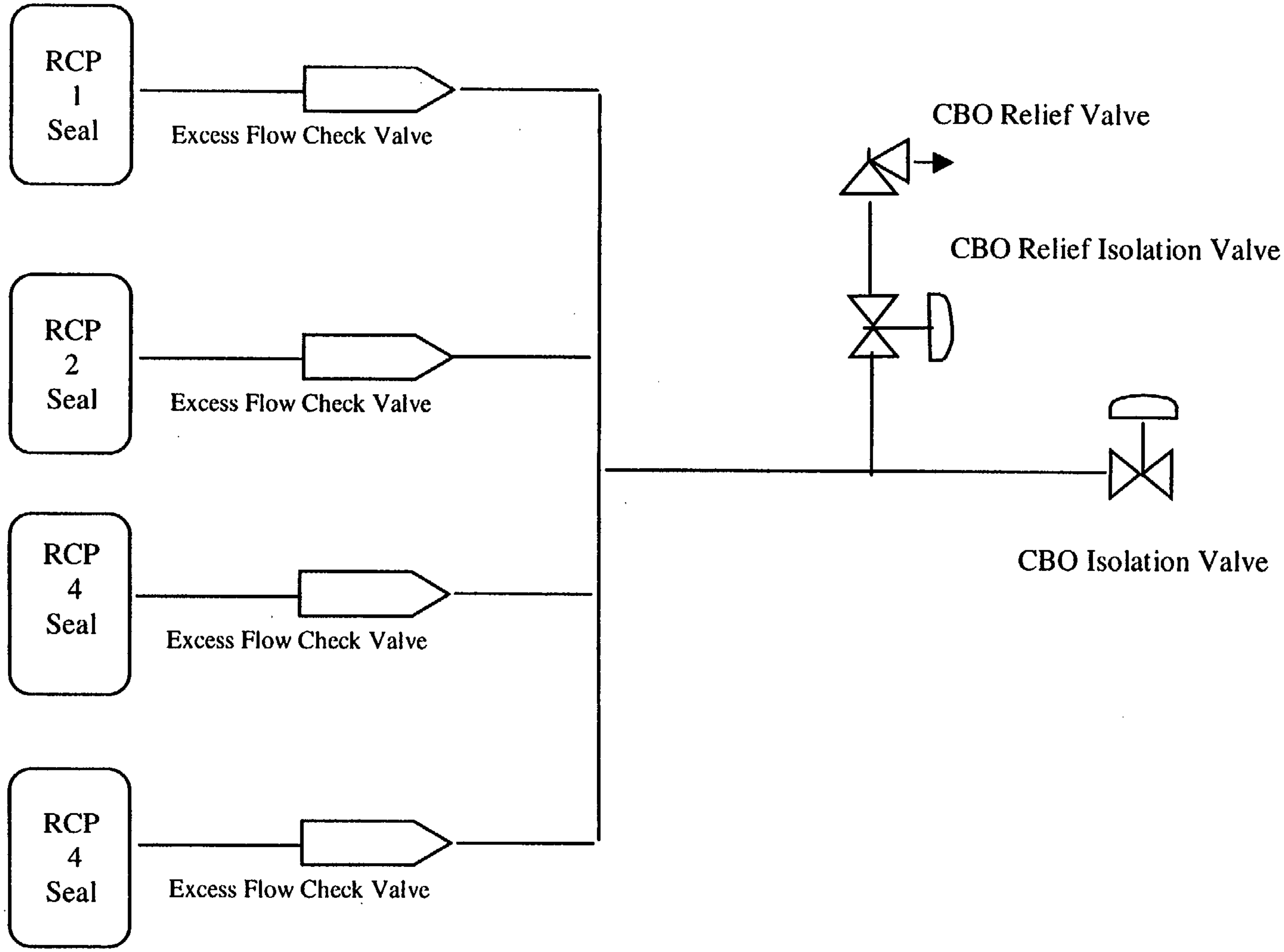
The CBO lines from the individual RCPs join in a common line, which contains the CBO isolation valve. This common line also includes a CBO relief valve, which will lift to relieve pressure in the CBO lines if the CBO isolation valve inadvertently closes. There is a CBO relief valve isolation valve between the CBO line and the CBO relief valve. This valve, in conjunction with the CBO isolation valve, provides the ability to fully isolate CBO flow if desired. Table 3.3-1 lists the set pressures and the flow capacities for the CBO relief valves at CE plants.

Table 3.3-1
CBO Relief Valve Set Pressures and Flow Capacities

Plant	Set Pressure (psig)	Flow Capacity (gpm)
Arkansas 2	150	
Calvert Cliffs 1 & 2	150	20
Ft. Calhoun	150	69
Millstone 2	250	20
Palisades	145	20
Palo Verde 1, 2 & 3	225	22
San Onofre 2 & 3	150	20
St Lucie 1 & 2	150	20
Waterford 3	150	20

The following points should be noted: (1) the CBO relief valve set flow and pressures are designed such that a challenge to the relief valve will not occur unless the first three stages of more than one RCP seal has failed (See Section 5.0) and (2) the relief valve on the CBO system may be isolated from the seal should it become necessary to terminate a high pressure discharge or an inadvertent opening of the relief valve.

Figure 3.3-1
Typical CBO Configuration for a CE Plant



3.4 Use of Elastomers in RCP Seals

Elastomers play a crucial role in the design and robustness of the RCP seal. Elastomers are used to establish separation of different materials and ensure the tight clearances required for seal operation are maintained. Seal materials used in early RCP seal designs were selected based primarily on normal seal operating conditions , not long term survivability at elevated temperatures. Materials used in the early SU seals included nitrile for design of U-cup inserts and ethylene-propylene for O-rings. Properties of seals vary based on material composition. A gross qualitative curve for elastomer classes "in general" is presented in Figure 3.4-1. The solid lines in the figure represent the generic material selection curves for nitrile and ethylene-propylene elastomers. As may be seen, nitrile compounds are less likely to survive exposure to a harsh environment than are ethylene-propylene compounds. Typically, the upper end for usability of nitrile compounds is ~ 250 °F. Temperatures much greater than that will result in rapid elastomer disintegration. (Note: the actual curves presented in the figure are only qualitative in that the elastomer compounds may be adjusted to provide greater temperature resistance. For example, ethylene-propylene elastomers may be procured for long term environments up to 400 °F). Following the advent of GI-23, changes were made to the seal design to increase the robustness to harsh environments. In particular, the new seal design for CE PWRs eliminated use of nitrile compounds and instead used ethylene-propylene derivatives.

Capabilities of the high temperature ethylene propylene used for RCP seals can be established by plotting results of experiments of these materials where material survivability (or failure) was observed during various experiments. As will be discussed in Section 7, long duration temperature experiments have been conducted on RCP seal elastomers by the industry. Several other tests have been performed by AECL. Survival and failure data obtained from US industry tests are superimposed on Figure 3.4-1[22]. The results clearly show that [

] The Kalsi Engineering Tests, contracted by SCE (Reference 13) clearly indicate a high likelihood of high temperature [(550 - 600 °F)] elastomer survivability for periods in excess of eight hours. Post-test inspections indicated that (even after [

] Similar conclusions may be drawn from inspection of BJ N-9000 seal test results.

Figure 3.4-1
Comparison of RCP Seal Elastomer Properties with "Industry" Elastomer Data

4.0 SEAL FAILURE MECHANISMS OF CONCERN

This section provides a qualitative discussion of the potential seal failure mechanisms associated with a loss of cooling to the RCP seals. Operational experience with various seal designs indicate that extended loss of seal cooling events are the only initiating events which can threaten seal integrity. The susceptibility of the various seals to these failure mechanisms vary among the seal designs, with a greater robustness expected in the later seal designs. Seal failure mechanisms are quantified in Section 9.

4.1 Operational Failure Mechanisms

Many seal stage failures occurred during the early years following initial plant startups for CE PWRs. Root cause analyses of these failures indicated that the vast majority of the failures were typically the result of faulty design, assembly or maintenance. Several seal stage failures were also attributed to a loss of cooling to one or more RCP seals. RCP seal failures can therefore 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 at PVNGS.

- 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, lack of quality control.

As plants matured and climbed the learning curve, most utilities learned how to treat the seals in such a way (both in maintenance and operation) as to maximize their useful life. In many cases the original seals were replaced with newly developed seals. Most of such seals were designed and developed with advanced computer techniques which did not exist when the original seals were designed.

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 loss of seal cooling initiating event.

4.2 Seal Failure Mechanisms Due To Loss of Seal Cooling

The Brookhaven National Laboratory (BNL) report "Guidance Document for Modeling of RCP Seal Failures[2] identifies and models three seal failure mechanisms associated with Loss of Component Cooling Water (LOCCW) 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 caused by fluid flashing.

The major concerns associated with the survivability of RCP seals during a loss of seal cooling 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 paragraphs briefly discuss each of these failure mechanisms.

4.2.1 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 part 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 loss of seal cooling conditions. This would result in the seal gap opening up and providing a leakage path.

A stage failure of this type appears to have occurred during the cooldown phase of extended LOCCW simulation. In that test[15] of an SU seal, the seal had been exposed to high temperature operation (400 °F) for more than 70 hours. Upon cooldown, the vapor seal lost its ability to hold pressure. Binding failure was not observed for any other stage. In a separate incident, a LOCCW event at MP2 with a four hour exposure of an SU seal to a 530 °F environment resulted in a seal stage failure most likely due to "cooking" the Nitrile U-cup (See Section 7).

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.

Table 4.2-1 discusses the factors that might contribute to the binding failure mechanism, how it might propagate from stage to stage, and its applicability to all five RCP seal cartridge types of concern. (Note: the upper stage row of Table 4.2-1 is not applicable to the 3-Stage seal design.)

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. Seal gaps associated with binding of the elastomer varies between 0.01 and 0.04 inches, depending on pump and seal design.

BNL[2] considered binding failure of the seal to be a concern only for low temperature ("unqualified") elastomers. BJ designs and Sulzer designs, particularly those typical of the current generation of RCP seals, are not expected to be significantly impacted by binding failure.

Table 4.2-1
Mechanical Binding RCP Seal Failure Mechanism

Stage	Loss of cooling conditions contributing to failure mechanism (Impact of CBO Isolation, RCP Status)	Impact of Failure Mechanism on Stage (What does Binding do to the stage leakage, mechanical condition / integrity, etc.)	How Failure Mechanism Affects Next Stage (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	How Failure Mechanism Affects Prior Stage (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	Overall Impact of Failure Mechanism on Seal Integrity
Lower Stage	With the pump stationary, neither CBO flow nor CBO isolation is expected to have any effect on the possibility of binding. Isolation of CBO flow (even without loss of cooling) with the pump running can lead to severe wear of the primary seal faces. This can generate particulate matter, which may lead to wear and binding in subsequent seal stages.	Mechanical binding will cause loss of staging (the seal stage will not hold its pressure differential). If the binding results in a cocked seal face, severe wear at the seal faces could result.	Mechanical binding will cause loss of staging (the seal stage will not hold its pressure differential). This forces the other stages to operate at higher-pressure differentials. If the binding results in a cocked seal face, severe wear at the seal faces could result in particulate matter, which could degrade subsequent seal stages.	N/A	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated).
Middle Stage	With the pump stationary, neither CBO flow nor CBO isolation is expected to have any effect on the possibility of binding. Isolation of CBO flow (even without loss of cooling) with the pump running can lead to severe wear of the primary seal faces. This can generate particulate matter, which may lead to wear and binding in subsequent seal stages.	Mechanical binding will cause loss of staging (the seal stage will not hold its pressure differential). If the binding results in a cocked seal face, severe wear at the seal faces could result.	Mechanical binding will cause loss of staging (the seal stage will not hold its pressure differential). This forces the other stages to operate at higher-pressure differentials. If the binding results in a cocked seal face, severe wear at the seal faces could result in particulate matter, which could degrade subsequent seal stages.	Mechanical binding in a stage will cause the other stages to carry a larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated).

Table 4.2-1
Mechanical Binding RCP Seal Failure Mechanism

Stage	Loss of cooling conditions contributing to failure mechanism (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	Impact of Failure Mechanism on Stage (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	How does failure mechanism affect next stage? (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	How does failure mechanism affect prior stage? (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	Overall Impact of Failure Mechanism on Seal Integrity
Upper Stage*	With the pump stationary, neither CBO flow nor CBO isolation is expected to have any effect on the possibility of binding. Isolation of CBO flow (even without loss of cooling) with the pump running can lead to severe wear of the primary seal faces. This can generate particulate matter, which may lead to wear and binding in subsequent seal stages.	Mechanical binding will cause loss of staging (the seal stage will not hold its pressure differential). If the binding results in a cocked seal face, severe wear at the seal faces could result.	Mechanical binding will cause loss of staging (the seal stage will not hold its pressure differential). This forces the other stages to operate at higher-pressure differentials. If the binding results in a cocked seal face, severe wear at the seal faces could result in particulate matter, which could degrade the vapor stage.	Mechanical binding in a stage will cause the other stages to carry a larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Vapor Stage	With the pump stationary, neither CBO flow nor CBO isolation is expected to have any effect on the possibility of binding. Isolation of CBO flow (even without loss of cooling) with the pump running can lead to severe wear of the primary seal faces.	Mechanical binding will cause loss of seal stage sealing and there will be external leakage. If the binding results in a cocked seal face, severe wear at the seal faces could result.	N/A	Slight re-staging of pressures across first 3 seals. CBO to VCT drops to zero as most of the CBO flow leaks to containment. Some CBO flow will go to the drain system.	Very undesirable to leak CBO to containment but will not have short-term effect on core uncovery.

* Upper stage is not applicable for the 3-Stage design

4.2.2 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 controlled bleedoff 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 loss of seal cooling.

Under loss of seal cooling conditions, the elastomers in each seal stages 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 4.2.1.

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. In several older plants with Westinghouse RCP seal systems, the secondary seal elastomers had a high probability of failure at temperatures greater than 500 °F. Current BJ and BWC seal designs at CE NSSS plants utilize O-rings with superior temperature performance and are consistent with the BNL qualified O-rings.

In practice, 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, the seal stages will heat up with the lower stages experiencing higher temperatures than the upper stages. If CBO flow is isolated, the temperature in a given stage will slowly increase due to heat conduction through the 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 may experience considerably greater temperatures than the upper seals, with the vapor seal experiencing the least adverse temperature environment.

It should be noted that in Section 2.2.1 of the "Guidance Document for Modeling of RCP Seal Failures" (Reference 2), BNL states that the nitrile compounds used in Byron Jackson static and secondary seals are not expected to fail due to high temperature extrusion. BNL also stated that for a Bingham Willamette, now Sulzer, seal assembly, one O-ring in each stage of the assembly would experience gap and pressure conditions which could result in potentially significant extrusion failure if subjected to full system pressure during a loss of seal cooling event.

Failure of qualified O-rings is unlikely during a loss of seal cooling event. Therefore, the BNL model assumes that qualified O-rings will not fail under full system pressure. Typically, most B-J and all Sulzer component seals utilize qualified seals constructed of ethylene propylene.

Table 4.2-2 discusses the factors that might contribute to the elastomer degradation failure mechanism and how it might propagate from stage to stage for each of the five RCP seal cartridge types of concern.

Table 4.2-2
Elastomer/Material Failure RCP Seal Failure Mechanism:
BJ 4-STAGE SU SEAL CARTRIDGE

Stage	Loss of cooling conditions contributing to failure mechanism (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	Impact of Failure Mechanism on Stage (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	How does failure mechanism affect next stage? (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	How does failure mechanism affect prior stage? (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	Overall Impact of Failure Mechanism on Seal Integrity
Lower Stage	U -cup, 2 O-rings Temp: >250 F and Pressure: >1500 psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of elastomer (U-cup) could lead to binding. When the shaft moves down (during depressurization of RCS), the rotating seal face cannot move up to remain mated to the stationary seal face.	Failure of elastomer seals leads to loss of staging. This forces the second and third stages to carry larger pressure drop.	N/A	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated).
Middle Stage	U -cup, 2 O-rings Temp: >250 °F and Pressure: >1500-psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of elastomer (U-cup) could lead to binding. When the shaft moves down (during depressurization of RCS), the rotating seal face cannot move up to remain mated to the stationary seal face.	Failure of elastomer seals leads to loss of staging in the middle stage. This forces the first and third stages to carry larger pressure drop.	Failure of elastomer seals leads to loss of staging in the middle stage. This forces the first and third stages to carry larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated).

Table 4.2-2 Elastomer/Material Failure RCP Seal Failure Mechanism: BJ 4-STAGE SU SEAL CARTRIDGE					
Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Upper Stage	U -cup, 2 O-rings Temp: >250 °F and Pressure: >1500 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well a higher equilibrium temperature. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of elastomer (U-cup) could lead to binding. When the shaft moves down (during depressurization of RCS), the rotating seal face cannot move up to remain mated to the stationary seal face.	No significant effect on pressure to vapor seal if the upper seal and even one of the prior stages fail to stage. Some temperature increase if malfunctioning seal(s) generate(s) heat. If all three first stages fail to stage, the vapor stage would be challenged.	Failure of elastomer seals leads to loss of staging in the upper stage. This forces the first and second stages to carry larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Vapor Stage	U -cup, O-ring Temp: >250 °F and Pressure: >200 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well as a higher equilibrium temperature since the hot CBO flow will introduce more heat. Without CBO flow the vapor stage would lose heat to the ambient. Pump running will accelerate seal failure and may result in a more severe failure. The vapor stage is designed to withstand full system pressure in a non-rotating condition.	Extrusion of elastomer (U-cup) could lead to binding. When the shaft moves down (during depressurization of RCS), the rotating seal face cannot move up to remain mated to the stationary seal face.	N/A	Slight re-staging of pressures across first 3 seals. CBO to VCT drops to zero as most of the CBO flow leaks to containment. Some CBO flow will go to the drain system.	Very undesirable to leak CBO to containment but will not have short-term effect on core uncovery.

Table 4.2-2 Elastomer/Material Failure RCP Seal Failure Mechanism: BJ 4-STAGE N-9000 SEAL CARTRIDGE and BJ 4-STAGE N-9000 SEAL CARTRIDGE with Type SU Seal Vapor Stage					
Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Lower Stage	2 Quad-rings, 4 O-rings Temp: > 300 °F Pressure: >1500 psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of elastomer Quad-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	Failure of elastomer seals leads to loss of staging. This forces the next 2 stages to carry larger pressure drop.	N/A	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Middle Stage	2 Quad-rings, 4 O-rings Temp: > 300 °F Pressure: >1500 psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of elastomer Quad-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	Failure of elastomer seals leads to loss of staging. This forces the third stage to carry larger pressure drop.	Failure of elastomer seals leads to loss of staging. This forces the first and third stages to carry larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)

Table 4.2-2
Elastomer/Material Failure RCP Seal Failure Mechanism:
BJ 4-STAGE N-9000 SEAL CARTRIDGE and BJ 4-STAGE N-9000 SEAL CARTRIDGE with Type SU Seal Vapor Stage

Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Upper Stage	2 Quad-rings, 4 O-rings Temp: > 300 °F Pressure: >1500 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well a higher equilibrium temperature. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of elastomer Quad-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	No significant effect on pressure to vapor seal if the upper seal and even one of the prior stages fail to stage. Some temperature increase if malfunctioning seal(s) generate(s) heat. If all three first stages fail to stage, the vapor stage would be challenged.	Failure of elastomer seals leads to loss of staging. This forces the first 2 stages to carry larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Vapor Stage	2 Quad-rings, 4 O-rings Temp: > 300 °F Pressure: >200 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well as a higher equilibrium temperature since the hot CBO flow will introduce more heat. Without CBO flow the vapor stage would lose heat to the ambient. Pump running will accelerate seal failure and may result in a more severe failure. The vapor stage is designed to withstand full system pressure in a non-rotating condition.	Extrusion of elastomer Quad-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	N/A	Slight re-staging of pressures across first 3 seals. CBO to VCT drops to zero as most of the CBO flow leaks to containment. Some CBO flow will go to the drain system.	Very undesirable to leak CBO to containment but will not have short-term effect on core uncovery.

Table 4.2-2
Elastomer/Material Failure RCP Seal Failure Mechanism:
SULZER 4-STAGE SEAL CARTRIDGE

Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Lower Stage	9 O-rings, 1 back-up ring Temp: > 300 °F Pressure: L > 1500 psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	Failure of the elastomer seals leads to loss of staging. This forces the second and third stages to carry a larger pressure drop.	N/A	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Middle Stage	9 O-rings, 2 back-up rings Temp: > 300 °F Pressure: L > 1500 psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	Failure of the elastomer seals leads to loss of staging. This forces the first and third stages to carry a larger pressure drop.	Failure of the elastomer seals leads to loss of staging. This forces the first and third stages to carry a larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)

Table 4.2-2
Elastomer/Material Failure RCP Seal Failure Mechanism:
SULZER 4-STAGE SEAL CARTRIDGE

Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Upper Stage	9 O-rings, 2 back-up rings Temp: > 300 °F Pressure: > 1500 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well a higher equilibrium temperature. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	No significant effect on pressure to vapor seal if the upper seal and even one of the prior stages fail to stage. Some temperature increase if malfunctioning seal(s) generate(s) heat. If all three first stages fail to stage, the vapor stage would be challenged.	Failure of the elastomer seals leads to loss of staging. This forces the first and second stages to carry a larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Vapor Stage	9 O-rings, 2 back-up rings Temp: > 300 °F Pressure: > 400 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well as a higher equilibrium temperature since the hot CBO flow will introduce more heat. Without CBO flow the vapor stage would lose heat to the ambient. Pump running will accelerate seal failure and may result in a more severe failure. The vapor stage is designed to withstand full system pressure in a non-rotating condition.	Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	N/A	Slight re-staging of pressures across first 3 seals. CBO to VCT drops to zero as most of the CBO flow leaks to containment. Some CBO flow will go to the drain system.	Very undesirable to leak CBO to containment but will not have short-term effect on core uncovery.

Table 4.2-2
Elastomer/Material Failure RCP Seal Failure Mechanism:
SULZER 3-STAGE SEAL CARTRIDGE

Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Lower Stage	9 O-rings, 1 back-up ring Temp: > 300 °F Pressure: L > 1500 psig will contribute to seal degradation. Lack of CBO Isolation should have no effect on seal degradation since rapid temperature rise will occur in either case. Pump running is a more severe condition since it is a dynamic condition and even more heat is generated. Pump running with isolated CBO flow will greatly accelerate seal failure.	Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	Failure of the elastomer seals leads to loss of staging. This forces the second and third (vapor) stages to carry a larger pressure drop.	N/A	Degraded seal integrity. Some increase in CBO flow (If CBO is not isolated).
Middle Stage		Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	No significant effect on pressure to vapor seal if the middle seal fails to stage. Some temperature increase if malfunctioning seal generates heat. If both two first stages fail to stage, the vapor stage would be challenged.	Failure of the elastomer seals leads to loss of staging. This forces the first and third (vapor) stages to carry a larger pressure drop.	Degraded seal integrity. Some increase in CBO flow (If CBO is not isolated).

Table 4.2-2
Elastomer/Material Failure RCP Seal Failure Mechanism:
SULZER 3-STAGE SEAL CARTRIDGE

Stage	**Loss of cooling conditions contributing to failure mechanism** (What elastomers are potentially affected, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What would failure of various elastomers of interest do to the stage leakage, mechanical condition / integrity, etc)	**How does failure mechanism affect next stage?** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**How does failure mechanism affect prior stage?** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Vapor Stage	9 O-rings, 2 back-up rings Temp: > 300 °F Pressure: > 400 psig will contribute to seal degradation. Lack of CBO Isolation will result in faster temperature rise as well as a higher equilibrium temperature since the hot CBO flow will introduce more heat. Without CBO flow the vapor stage would lose heat to the ambient. Pump running will accelerate seal failure and may result in a more severe failure. The vapor stage is designed to withstand full system pressure in a non-rotating condition.	Extrusion of the secondary seal back-up ring or the associated secondary seal O-ring could lead to binding when the shaft moves down (during depressurization of RCS) and the stationary seal face cannot follow to remain mated to the rotating seal face.	N/A	Slight re-staging of pressures across first 2 seals. CBO to VCT drops to zero as most of the CBO flow leaks to containment. Some CBO flow will go to the drain system.	Very undesirable to leak CBO to containment but will not have short-term effect on core uncovery.

4.2.3 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. Table 4.2-3 discusses the factors that might contribute to the hydraulic instability (pop-open) failure mechanism and how it might propagate from stage to stage and is applicable to all RCP seal cartridge types of concern (NOTE: the upper stage row of Table 4.2-3 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. CE plants utilize a variety of seal designs that include parallel face hydrodynamic seals. 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 with the seal gap. Flashing in the gap will also change the pressure distribution within the seal face. Analytical models developed by AECL[28] 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 term coined 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 that 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), 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. Intermittent and sustained seal "pop-open" events have been observed during tests of BJ SU seals (See Section 6.0). The "pop-open" behavior was often transitory and impacted only certain seals. Evidence of local seal "pop-open" has been noted in operational loss of seal cooling events at various CE PWR plants (See Section 7.0). Generally, "pop-open" events have propagated to stage failures when extended exposure of seals to high temperature liquid aggravated the "pop-open" process by making it more difficult for the seal to reclose once the dynamic condition has been removed. To date the only evidence of seal "pop-open" in CE PWRs has been limited to BJ/SU seals. In the early 80's, RCP manufacturers redesigned the RCP seal cartridge to be more robust to the adverse conditions following station blackout events. Discussions with the RCP seal vendors has indicated that improved materials resulted in improved gap closure during static pump conditions and reduced the potential for significant seal face flaws. This reduced the potential for a "pop-open" event.

Table 4.2-3
Hydraulic Instability (Pop-Open) RCP Seal Failure Mechanism

Stage	**Loss of cooling conditions contributing to failure mechanism** (What temperature and pressure are required, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What is the impact of instability / pop-open on the stage integrity, leakage, mechanical condition, etc? Is condition potentially self-healing?)	**Impact of Failure Mechanism on Next Stage** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**Impact of Failure Mechanism on Prior Stage** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Lower Stage	"Flashing" of the liquid to steam may occur when the pressure between the seal faces drops and sub-cooling is lost. When the RCP is running with CBO flow and loss of cooling, more heat is introduced and there is a pressure drop across the seal. When the RCP is stopped and CBO flow is isolated the pressures will be higher; there will be no pressure differential across the seal faces. This should reduce the opportunity for flashing. Note: SU-type seals have a tendency to "chatter" (rapid pressure oscillations within one or more of the seal cavities) when the CBO fluid is too cold.	"Pop-open" will cause loss of staging (the seal stage will not hold its pressure differential). If the "pop-open" is a dynamic condition resulting in "chattering," it will lead to accelerated wear of the seal faces and the Quad-ring. Unless the pop-open results in binding, the seals may self-heal re-establishing normal pressure breakdown (if CBO flow is not isolated). If CBO flow is isolated there should be no cause for pop-open.	"Pop-open" will cause loss of staging (the seal stage will not hold its pressure differential). This forces the other stages to operate at higher-pressure differentials. In a running pump, if the "pop-open" results in binding with a cocked seal face, severe wear at the seal faces could result in particulate matter which could degrade subsequent seal stages.	N/A	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated).
Middle Stage	"Flashing" of the liquid to steam may occur when the pressure between the seal faces drops and sub-cooling is lost. When the RCP is running with CBO flow and loss of cooling, more heat is introduced and there is a pressure drop across the seal. When the RCP is stopped and CBO flow is isolated the pressures will be higher; there will be no pressure differential across the seal faces. This should reduce the opportunity for flashing. Note: SU-type seals have a tendency to "chatter" (rapid pressure oscillations within one or more of the seal cavities) when the CBO fluid is too cold.	"Pop-open" will cause loss of staging (the seal stage will not hold its pressure differential). If the "pop-open" is a dynamic condition resulting in "chattering," it will lead to accelerated wear of the seal faces and the Quad-ring. Unless the pop-open results in binding, the seals may self-heal re-establishing normal pressure breakdown (if CBO flow is not isolated). If CBO flow is isolated there should be no cause for pop-open.	"Pop-open" will cause loss of staging (the seal stage will not hold its pressure differential). This forces the other stages to operate at higher-pressure differentials. In a running pump, if the "pop-open" results in binding with a cocked seal face, severe wear at the seal faces could result in particulate matter which could degrade subsequent seal stages.	"Pop-open" in a stage will cause the other stages to carry a larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated).

Table 4.2-3
Hydraulic Instability (Pop-Open) RCP Seal Failure Mechanism

Stage	**Loss of cooling conditions contributing to failure mechanism** (What temperature and pressure are required, Impact of CBO Isolation, RCP Status)	**Impact of Failure Mechanism on Stage** (What is the impact of instability / pop-open on the stage integrity, leakage, mechanical condition, etc? Is condition potentially self-healing?)	**Impact of Failure Mechanism on Next Stage** (Can failure propagate upward? Can it influence potential for other failure mechanisms in next stage.)	**Impact of Failure Mechanism on Prior Stage** (Can failure propagate downward? Can it influence potential for other failure mechanisms in prior stage.)	**Overall Impact of Failure Mechanism on Seal Integrity**
Upper Stage*	"Flashing" of the liquid to steam may occur when the pressure between the seal faces drops and sub-cooling is lost. When the RCP is running with CBO flow and loss of cooling, more heat is introduced and there is a pressure drop across the seal. When the RCP is stopped and CBO flow is isolated the pressures will be higher; there will be no pressure differential across the seal faces. This should reduce the opportunity for flashing. Note: SU-type seals may have pressure oscillations within one or more of the seal cavities when the CBO fluid is too cold.	"Pop-open" will cause loss of staging (the seal stage will not hold its pressure differential). If the "pop-open" is a dynamic condition resulting in "chattering," it will lead to accelerated wear of the seal faces and the U-cup. Unless the pop-open results in binding, the seals may self-heal re-establishing normal pressure breakdown (if CBO flow is not isolated). If CBO flow is isolated there should be no cause for pop-open.	"Pop-open" will cause loss of staging (the seal stage will not hold its pressure differential). This forces the other stages to operate at higher-pressure differentials. In a running pump, if the "pop-open" results in binding with a cocked seal face, severe wear at the seal faces could result in particulate matter which could degrade the vapor seal stage.	"Pop-open" in a stage will cause the other stages to carry a larger pressure drop.	Slightly degraded seal integrity. Slight increase in CBO flow (If CBO is not isolated)
Vapor Stage	"Flashing" of the liquid to steam may occur when the pressure between the seal faces drops and sub-cooling is lost. When the RCP is running with CBO flow and loss of cooling, more heat is introduced and there is a pressure drop across the seal. When the RCP is stopped and CBO flow is isolated the pressure will be higher. This should reduce the opportunity for flashing; also, the vapor stage loses a lot of heat to the ambient.	"Pop-open" will cause loss of the sealing capability. If the "pop-open" is a dynamic condition resulting in "chattering," it will lead to accelerated wear of the seal faces and the U-cup. Unless the pop-open results in binding, the seals may self-heal re-establishing normal sealing function.	N/A	Slight re-staging of pressures across first 3 seals. CBO to VCT drops to zero as most of the CBO flow leaks to containment. Some CBO flow will go to the drain system.	Very undesirable to leak CBO to containment but will not have short-term effect on core uncovery.

* Upper stage is not applicable to the 3-Stage design.

5.0 OPERATION CONSIDERATIONS AFFECTING SEAL PERFORMANCE

The basic design and general capabilities of RCP seals in CE NSSS plants are similar, and do not appreciably affect the general seal failure mechanisms. However, the details of their design will impact the specific seal failure probability and potential leakage. To understand the seal failure model presented in Section 8.0, several aspects of normal and abnormal seal operation plant and post accident response to loss of seal cooling events should be highlighted. These items are described in the following paragraphs.

5.1 Pressure Staging of RCP seals for CE PWRs

RCPs at CE plants utilize multistage hydrodynamic seals. With the exception of Palo Verde, all RCP seals include three lower seal stages and a fourth vapor seal stage. Each seal stage normally operates with an equal pressure drop, accomplished by bleeding a bypass flow through pressure breakdown devices which are in parallel with each seal stage. A fourth vapor seal provides an additional pressure barrier. Each seal stage is normally operated at about 130 - 180 °F. All seal stages are capable of holding full system pressure at 250 °F for a limited time period.

The Palo Verde RCPs utilize a three stage seal; the seals are staged such that 43% of the pressure drop occurs across each of the first two PBDs and 14% is taken across a system orifice.

The pressure drop across any seal in staged seals is maintained by a controlled bleedoff flow from the RCS. For example, a CBO flow of 1 gpm in BJ RCP seals creates a pressure drop of ~700 psig across the lower three seal stages. The vapor seal stage normally operates in the 25 to 100 psig range. In the Palo Verde design, a 3 gpm CBO is designed to produce a pressure difference of 968 psig across each of the two lowermost seal faces. The vapor seal is operated at a pressure difference of 315 psig. The PBDs are designed such that the CBO flow is very small, < 3 gpm. (See Figures 3.2.1-1 and 3.2.2-1)

5.2 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 offered by the open (failed) seal. Consequently, the seals will restage (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. Tables 5.2-1 and 5.2-2 illustrate the expected leakage from 4 and

3 stage RCP seals, respectively. When the vapor seal is intact, the increased flow will be primarily directed towards the CBO line. Otherwise, a seal leakage will be noted and the excess flow will be sensed in the containment.

Table 5.2-1:
Summary Impact Of Stage Failures for a 4-Stage Seal Design*

STAGES FAILED	CBO INCREASE**	COMMENTS
Vapor seal (with others intact)	[ ]	No PBDs bypassed. Minor leakage of CBO flow into Reactor Drain Tank (RDT).
Any one of first three stages (with or without vapor seal intact)	[ ]	Increased flow will be directed to CBO line if vapor seal intact.
Any two of first three stages (with or without vapor seal intact)	[ ]	Increased flow will be directed to CBO line if vapor seal intact.
Three lower PBD controlled seals failed catastrophically. Vapor seal intact	Plant specific – see Table 5.2-3	Flow is limited by excess flow check valve and/or relief valves (see section 3.4). CBO line may be isolated. With vapor seal intact and CBO line/relief valves not isolated, excess leakage is directed to the CBO line and out the relief valve.
All seals failed catastrophically	Plant specific – see Table 5.2.3	With vapor seal failed excess leakage is directed to the CBO line and out the relief valve.

* No seal leakage occurs into containment if vapor seal is intact.
** Based on 1.0 gpm nominal flow

Table 5.2-2:
Summary Impact Of Stage Failures for the PVNGS 3-Stage Seal Design*

STAGES FAILED	CBO INCREASE**	COMMENTS
Vapor seal (or Stage III)	[ ]	Seal restaged such that the vapor stage pressure drops too ambient and each stage takes 50% of pressure drop.
Seal I or II failed	[ ]	Flow increase reflects loss of 43% of initial flow path resistance.
Two seals failed (I & III or II & III)	[ ]	Flow increase reflects loss of 57% of initial flow path resistance.
Two seals failed (I & II)	[ ]	Flow increase reflects loss of 86% of initial flow path resistance.
All seals failed catastrophically***	[ ]	Base on RELAP analysis (Reference 20)

* No seal leakage occurs into containment if vapor seal is intact.
** Based on 3.2 gpm nominal flow
*** Low leakage is a combined result of highly restrictive shaft gaps and limited possible shaft motion (< 0.01 inches). PVNGS Sulzer Bingham Calculation E12.5.387 Rev 1 section 4.0 assumes a 0.01-inch gap clearance between the RCP seal faces for each of the three seals representing a degraded seal condition. When the RCP is not running, the shaft will not drop until RCS pressure is reduced below 50 psia.

Full catastrophic failure of the RCP seal stages would significantly reduce the hydraulic resistance between the RCS and the containment. The resulting RCS inventory loss may be bounded by assuming that the RCP thermal barrier flow area limits the discharge rate. These flows have been previously established for several CE plants utilizing various BJ 4 stage RCP seals (See Table 5.2-3). These values are considered generally valid for the current BJ design RCPs in CE PWRs since they do not credit the additional resistances associated with the downstream seal. The presence of narrower passages or additional resistance would reduce these leakage rates, however, a detailed review of the additional flow restrictions has not been performed.

The PVNGS units are designed with the CE-KSB pump. A recent analysis performed for the PVNGS Sulzer 3-stage seal design indicates the existence of both a very small shaft gap (typical of the CE-KSB pump design) and significantly lower seal failure gaps. The catastrophic failure analysis in all seals considered a limited seal gap opening of 0.01 inches. The resulting RCS leakage was estimated to [ ]. The actual flow was limited by choking in the seal gap.

Table 5.2-3
Leakage Through RCP Thermal Barrier

PLANT	RCP Design	MIN. AREA + THERMAL BARRIER*	K-factor*	LEAKAGE (GPM) @ 2300 psia
Fort Calhoun Station	BJ	[ ]	[ ]	[ ]
Calvert Cliffs 1& 2	BJ**	[ ]	[ ]	[ ]
SONGS 2 & 3 and WSES (BJ design)	BJ**	[ ]	[ ]	[ ]
Palo Verde	KSB	[ ]	[ ]	[ ]

* Nominal hydraulic resistance (From CE-NPSD-657-P, Ref 23)
** Seals not currently used in plant design

Note that multiple failures are required for any significant leakage to occur. For the 4-stage RCP seal design all three lower stages must fail to get RCS leakage [ ] gpm. Failure of four stages will result in significant leakage into the containment. For the three stage RCP seal design, all stages must fail for RCS leakage to [ ] gpm per pump.

Failure of three lower stages will result in complete bypass of the PBDs. This will result in pressurization of the last seal cavity and a challenge to the CBO relief valve. The excess flow check valve in the CBO line is designed to limit RCS leakage to about 15 gpm per pump. Cumulative leakage (multiple RCP leakage) is limited by the CBO relief valve (See Table 3.3-1).

It should also be noted that the leakage flow is dependent upon RCS pressure. The estimates for the four stage seals in Table 5.2-3 assume the RCS is at normal operating pressure with no downstream resistance considered.

These results suggest that, provided one lower seal stage remains operable, the seal leakage may be controlled by the normal CVCS. Plants with a four stage seal cartridge design that experience a concurrent loss of three seal stages (with one lower stage operable) will develop an increased RCS leakage flow of [ ] gpm, assuming the plant is at full system pressure. When the vapor seal is intact, this leakage will be directed through the CBO line to the VCT; when the vapor seal is failed, the leakage will be directed to the containment.

Similarly, three stage seal designs where two seal stages are non-functional will produce an enhanced RCS leakage of [ ] gpm per seal at nominal RCS pressure. As in the 4 stage seal design, integrity of the vapor stage will determine the direction of the RCS leakage. As RCS pressure diminishes, so will the attendant leakage. Even under the most adverse circumstances, a sustained [ ] gpm for a period of 8 hours will result in a loss of [ ] gallons of RCS. It is estimated that an inventory loss of approximately 35,000 gallons is necessary before incipient core uncovery in even the smallest of CE PWRs. 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 Loss of Coolant Accident (LOCA).

5.3 RCP Seal Conditions Following Loss of Seal Cooling Events

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 loss of seal cooling events on seal performance it is useful to understand the post-accident thermal-hydraulic performance of the RCP seal cartridge of a typical CE PWR, and the range of potential actions that may be taken by the plant staff in responding to these events. It is the intent of this section to explore the post-accident seal environmental conditions that would precede seal degradation. Issues associated with accident mitigation following a seal failure are briefly discussed in Section 6.3.2.

CE plants employ two classes of seal cooling systems. CE PWRs with four stage seals typically have a single system for providing shaft lubrication and seal cooling. In this system RCS coolant is drawn into the seal and cooled to between 120 and 140 °F by a seal cooling heat exchanger. Seal cooling water to the heat exchanger is typically provided by the component cooling water system. Once the RCS leakage is cooled, the resulting coolant is allowed to pass through the seals and up the RCP shaft. For CE plants that utilize three stage seals, the seal heat exchanger cooling loop is supplemented by an independent seal injection system. As a consequence of the difference in seal cooling designs there is a slight difference in how loss of seal cooling is defined at the various plants. In this context, loss of seal cooling applies to the total loss of cooling to the RCP seal. Therefore, for the three stage seal design, loss of cooling implies loss of both the CCW and the injection pathways to the heat exchanger.

Loss of cooling to an RCP seal can occur in the following ways:

1. Station blackout (loss of offsite power and inoperability of all plant diesels) causing a total loss of all seal cooling.

2. Loss of component cooling water system affecting seal heat exchanger heat removal. These failures will typically result in loss of seal cooling to more than one RCP.

3. Loss of seal cooling to one or more RCP seals due to the inoperability of one or more seal heat exchanger cooling control valve(s).

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

5.3.1 Seal Conditions during a Station Blackout Event

All RCP seal coolant systems (injection and recirculation type) require power to operate the pumps to remove RCS heat from the seal. A Station blackout (SBO) event implies a complete loss of AC power. Station blackout 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 steam generators during an SBO operators have limited control of plant dynamics. ADVs and sufficient secondary side condensate will be available to effect a SG cooldown. EOPs instruct the operator to maintain the plant in a stable condition with an RCS subcooling of between 20 and 50 °F. In practice, plant depressurization much below that of the MSSV setpoint will not be attempted since inventory makeup for the additional shrinkage is not available.

Closure of the CBO line during a SBO is dependent on the motive source for the valve operator and plant procedures. Plants with DC powered CBO line valve MOVs or air operated valves can elect to close the CBO line. 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 (approximately 1000-1200 psia). The RCS temperature [ ] will be about 500 to 540 °F.

The actual seal temperature distribution will depend on the time of the CBO flow isolation. The residual heat capacity in the seal heat exchanger and structure will delay the seal temperature heat-up. Results from LOSC experiments suggest that early isolation of CBO (in less than 5-10 minutes) ensure that seal temperatures at all upper seal cavities will be maintained [ ] (cf., Reference 17). At these temperatures no serious threat exists for seal failure. Delayed isolation of CBO flow will allow the lower seal cavities to heat up to temperatures near that of the RCS. The vapor stage is the uppermost seal and is less isolated from ambient heat losses than the lower stages, consequently, this stage experiences a lesser equilibrium heatup. Typically, temperatures in the vapor stage [ ] below that of the lower RCP seal stages, depending upon RCP design. This factor is important to take into consideration when estimating whether flashing may or may not occur.

Table 5.3-1 Vapor Stage and RCP Seal Lower Cavity Equilibrium Heatup Temperatures		
RCP and seal design	**Temperature of lower seal stages (°F)**	**Temperature of vapor seal (°F)**
BJ RCPs 4 stage Seals	[ ]	[ ]
CE-KSB Pumps	[ ]	[ ]

During the station blackout test performed on the N-9000 seal cartridge[8], it was found that the third seal stage ran cooler because a lot of heat was being lost to the ambient air.

Based on the above considerations, three representative temperature distributions were generated for each of the three and four stage seal designs. In developing Table 5.3-2, system pressures and temperatures were selected based on approximate values of the MSSV setpoints and normal RCS operating temperatures for the reactor class. Late isolation of CBO will also impact the seal heatup and the final equilibrium temperature. Experimental observations from the BJ N-9000 SBO test[17] indicate that even when CBO is isolated 1.5 hours into the event the local ambient temperature in the lower seals will [ ]. A greater temperature drop is expected in the vapor seal. The SG setpoint was assumed to be 1200 psia (representative of Palo Verde Units) for the three stage seal design; four stage seal designs were analyzed at an RCS pressure of 1000 psia.

Table 5.3-2a 4-Stage Seal Design Representative Post-Accident Conditions following a SBO Event						
	CBO ISOLATED EARLY		**CBO ISOLATED LATE**		**CBO NOT ISOLATED**	
	Pressure psia	**Temperature °F**	**Pressure psia**	**Temperature °F**	**Pressure psia**	**Temperature °F**
Seal Cavity 1	1000	[ ]	1000	[ ]	[ ]	[ ]
Seal Cavity 2	1000	[ ]	1000	[ ]	[ ]	[ ]
Seal Cavity 3	1000	[ ]	1000	[ ]	[ ]	[ ]
Vapor Seal	1000	[ ]	1000	[ ]	[ ]	[ ]

Table 5.3-2b 3-Stage Seal Design Representative Post-Accident Conditions following a SBO Event						
	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1200	[ ]	1200	[ ]	[ ]	[ ]
Seal Cavity 2	1200	[ ]	1200	[ ]	[ ]	[ ]
Vapor Seal	1200	[ ]	1200	[ ]	[ ]	[ ]*

* Saturation temperature, See Reference 8.

It should be noted that when establishing the RCS subcooling, the RCS temperature is set equal to the core exit (or hot side conditions). This is done by using the hot leg RTDs or the core exit thermocouple temperatures. Thus, when maintaining subcooling additional subcooled margin is available when considering the subcooling at the RCP.

5.3.2 Seal Conditions during a Loss of Component Cooling Water Event

Coolant for the RCP seal heat exchanger typically is supplied by the component cooling water or other cooling water system. Failure of all or portions of this system that supply heat removal to the RCP seal heat exchanger will result in a loss of cooling to the affected pumps. Unlike the SBO event loss of seal cooling to the RCP does not automatically cause a shutdown of the affected pump. Before the RCP will be shut down, the operator must identify the loss of seal cooling and take proceduralized actions that deal with this event. However, once the affected RCPs are secured, the operator has the full resources of the plant (that is those resources not impacted by the specific loss of CCW event) to manage the event.

Detection of global and partial loss of cooling events should be straight forward. CE plants are equipped with numerous means to indicate when loss of seal cooling has occurred. In addition to the status information / alarms associated with the LOCCW event, the operator can also identify loss of seal cooling through component-specific accident indicators and alarms. These include sensing CBO seal outlet temperature and, in some instances, seal stage temperatures. 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. A typical time required from the onset of a loss of seal cooling event for the operator to diagnose the event and trip the RCP is under 10 minutes. Experiments and experience have consistently shown that RCP seals will operate successfully for more than 30 minutes without cooling.

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

1. Actions for and timing of CBO isolation.

2. Actions for and timing of return of seal cooling.

Proceduralized operator actions following a loss of seal cooling vary among CEOG utilities. Of particular importance to the loss of seal cooling event is the likelihood that operator will isolate CBO, depressurize the RCS, and return CCW to operation.

The post accident strategy for coping with loss of RCP seal cooling varies among CE PWRs (See Table 5.3-3). The recommended procedure is to trip the pumps as early into the loss of cooling event as possible, on the order of 2 - 5 minutes. Once tripped, the pumps will coast down and come to a stop in about 3 to 4 minutes. Upon loss of seal cooling, many plants will isolate CBO in the affected pump. A controlled cooldown may or may not be conducted. In any event the RCS will be taken to a hot standby condition with the RCS subcooled. A controlled cooldown in these circumstances will take between six and eight hours. As the RCS cools, the RCP seal pressures will decrease accordingly as will the RCP temperatures. These actions will reduce the potential for, and severity of, a seal failure. During a cooldown, the operators will attempt to maintain a high RCS subcooling, typically greater than 50 °F (procedures only *require* a minimum of 20 °F subcooling in the hot leg).

Vendor guidance has resulted in procedures for preventing restoration of seal cooling to seals that have been uncooled for a period of more than (10 to 30 minutes). The basis for the delay is that restoration of cooling may degrade or further damage the RCP seals. (Note: This guidance was based on SU seal designs and plants with seal injection. It was intended to avoid thermal shock to seal components. For CE units with N-9000 seals, it is preferable to not allow a seal exposed for greater than 31 minutes without cooling to be exposed to many hours of elevated temperatures. The N-9000 seal is thermal shock resistant, and restoration of CCW is unlikely to cause any rapid cooldown in the seal cavity of an idle pump.)

Tables 5.3-4a through 5.3-4c and 5.3-5a through 5.3-5c provide representative seal conditions for seals various hot standby and RCS cooldown conditions.

Table 5.3-3
Summary of Post-Accident Operator Actions for Various CE PWRs

ACTION	PLANT								
	CCNP	PALISADES	FCS	SONGS	PVNGS	ANO2	WSES	SL 1&2	MP2
Isolate CBO on LOCCW?	No	IF: Note 7	No	No	No (Note 4)	Yes	No	Yes (30 minutes)	No (Note 8)
Isolate CBO on SBO?	No	Yes	No	Yes	Yes	Yes	No	Yes (30 minutes)	No (Note 9)
Depressurize RCS on LOCCW	Note 1	Not required	Optional	Hot Shutdown	Hot Standby	Cooldown	Optional	Shutdown	No (Note 8)
Depressurize RCS on SBO	Note 1	Not required	Unlikely per EOPs	Hot Shutdown	Hot Standby	Hot shutdown	Not likely	Hot Standby	No (Note 10)
Subcooling on LOCCW	>50 (2) very likely	> 25 required	20-50	>80	>50	>50 F	>50	20-30 (Note 5)	30 –60 (Note 11)
Subcooling on SBO	30-50	> 25 required	20-50	20-50	24 - 50	30-50 F	<50	20-30 (Note 5)	30 –60 (Note 11)
Max. Travel of Shaft	0.040	0.060	Not Available	0.025	0.030	0.065 (est.)(3)	0.04	<0.020	0.017 – 0.022 (Note 12)
RCS Pressure for RCP to Reseat	1100 psia	1000 psia	Not Available	700	50 (Note 6)	600	600 (approx.)	1100 - 1400	Not Available

Notes:

1. Dependent on availability of condensate and anticipated recovery
2. EOPs require 20-50 F° subcooled margin
3. Assumes travel from a 1500 psia hot standby condition to 600 psia
4. Isolate CBO on loss of CCW and seal injection (RCP Operating); CCW may be backed up by Essential Cooling Water System. Isolate CBO on loss of CCW or Seal injection (RCP shutdown)
5. Procedural – minimum: 20 °F, maximum: 200 °F.
6. 50 psi with RCP shutdown (LOCCW); 900 psi with RCP operating.
7. Yes, If:
   Any RCP seal or CBO temperature > 185 °F OR
   Any RCP bearing temperature > 175 °F, OR
   CCW to containment lost for > 10 minutes, OR
   All CCW pumps will not operate.
8. Procedure AOP 2564 directs tripping the reactor and stopping the affected RCPs and following EOP 2525, "Standard Post Trip Actions" (stabilize plant at Mode 3 NOP/NOT).
9. EOP 2530, "Station Blackout" directs that CBO containment isolation valve be closed, which isolates CBO flowpath to the VCT, however, the isolation valve upstream of the CBO relief valve is not closed. So, CBO flow will continue through this flowpath.
10. EOP 2530, "Station Blackout" directs establishment of natural circulation cooling and cooldown to achieve 30 to 60 °F of subcooling within the limits of the P/T curve for the existing pressure. Depressurization of RCS is the result of pressurizer level drop from ambient heat loss, inventory loss, and shrink due to cooldown.
11. EOP 2525, "Standard Post Trip Actions" directs maintaining greater than or equal to 30 °F of subcooling. It is very likely that 50 °F would be maintained..
12. The motor tech manual specifies a maximum calculated shaft movement of 0.060 inches between max external upthrust at rated speed (120000 lbs) and external downthrust at rated speed (65000 lbs). However, the specified axial end play is 0.017 to 0.022 inches.

Table 5.3-4a
4-Stage Seal Design
Representative Post-Accident Conditions following a LOCCW Event
Plant Placed In Hot Standby

	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure Psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1800	[ ]	1800	[ ]	[ ]	[ ]
Seal Cavity 2	1800	[ ]	1800	[ ]	[ ]	[ ]
Seal Cavity 3	1800	[ ]	1800	[ ]	[ ]	[ ]
Vapor Seal	1800	[ ]	1800	[ ]	[ ]	[ ]

Table 5.3-4b
4-Stage Seal Design
Representative Post-Accident Conditions following a LOCCW Event
Depressurized To 1500 Psia

	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure Psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1500	[ ]	1500	[ ]	[ ]	[ ]
Seal Cavity 2	1500	[ ]	1500	[ ]	[ ]	[ ]
Seal Cavity 3	1500	[ ]	1500	[ ]	[ ]	[ ]
Vapor Seal	1500	[ ]	1500	[ ]	[ ]	[ ]

Table 5.3-4c
4-Stage Seal Design
Representative Post-Accident Conditions following a LOCCW Event
Depressurized To 1200 Psia

	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure Psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1200	[ ]	1200	[ ]	[ ]	[ ]
Seal Cavity 2	1200	[ ]	1200	[ ]	[ ]	[ ]
Seal Cavity 3	1200	[ ]	1200	[ ]	[ ]	[ ]
Vapor Seal	1200	[ ]	1200	[ ]	[ ]	[ ]

Table 5.3-5a
3-Stage Seal Design
Representative Post-Accident Conditions following a LOCCW Event
Plant Placed In Hot Standby (RCS Pressure assumed = 1800 psia)

	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure Psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1800	[ ]	1800	[ ]	[ ]	[ ]
Seal Cavity 2	1800	[ ]	1800	[ ]	[ ]	[ ]
Vapor Seal	1800	[ ]	1800	[ ]	[ ]	[ ]

Table 5.3-5b
3-Stage Seal Design
Representative Post-Accident Conditions following a LOCCW Event
Depressurized To 1500 Psia

	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure Psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1500	[ ]	1500	[ ]	[ ]	[ ]
Seal Cavity 2	1500	[ ]	1500	[ ]	[ ]	[ ]
Vapor Seal	1500	[ ]	1500	[ ]	[ ]	[ ]

Table 5.3-5c
3-Stage Seal Design
Representative Post-Accident Conditions following a LOCCW Event
Depressurized To 1200 Psia

	CBO ISOLATED EARLY		CBO ISOLATED LATE		CBO NOT ISOLATED	
	Pressure psia	Temperature °F	Pressure Psia	Temperature °F	Pressure psia	Temperature °F
Seal Cavity 1	1200	[ ]	1200	[ ]	[ ]	[ ]
Seal Cavity 2	1200	[ ]	1200	[ ]	[ ]	[ ]
Vapor Seal	1200	[ ]	1200	[ ]	[ ]	[ ]

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. This tends to ensure a high level of subcooling is maintained at the seal faces and minimizes the pressure drops across the internal 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. The vapor seal will be exposed to the full system pressure drop, however, the seal is designed to withstand these pressures and temperatures for a time period in excess of 24 hours (Reference 14).

5.3.3 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 four stage seal design, internal stage failures will redistribute pressure as follows:

Table 5.3-6
Pressure Redistribution in a 4-Stage Seal
(RCS at 1800 psia)

	No Seal Failure	Stage 2 Failure	Stage 3 Failure
Seal Cavity 1	[ ]	[ ]	[ ]
Seal Cavity 2	[ ]	[ ]	[ ]
Seal Cavity 3	[ ]	[ ]	[ ]
Vapor Seal	[ ]	[ ]	[ ]

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 LOCCW example the entrance conditions will become saturated. On the other hand, when stage 2 fails in advance of stage three, the downstream cavity fluid becomes pressurized, increasing the seal stability.

In the case of a 3-stage seal, the impact of seal redistribution is less marked. For example, failure of seal stage 3 (vapor seal) will result in a seal pressure redistribution which, for hot standby conditions, will decrease the seal cavity pressure from [ ] to about [ ] psia. On the other hand, the middle seal failure results in a projected increase in the vapor seal pressure from [ ] psia. Thus, as with the 4-stage seal, downstream stage failures will decrease seal pressure and subcooling while upstream stage failures have the opposite effect.

The impact of pressure redistribution impacts the seal stage failure propagation and common cause conditions. Note that once a downstream seal stage has failed, failure of the upstream seal stage is increased (for all seals except the lowest seal stage).

5.3.4 Post-Accident 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 3.3-1, 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 and the CBO relief valve isolation valve must be closed. Regardless, CBO flow is limited by excess flow check valves which isolate CBO discharge from any single RCP seal.

5.4 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 components move downward or simply as a result of thermal expansion of seal and RCP components. Shaft motions were simulated in the BJ N-9000 SBO test. In that tests, the shaft motion varied from an axial position of 0.114 inches at 2200 psia to 0.07 inches at 1688 psia.

Potential relative gaps resulting from motions depend upon RCP seal designs. Typical potential seal gaps vary from 0.02 to 0.07 inches. For the Sulzer pump seal design for the Palo Verde units, seal gaps during RCS decompression are expected to be much less than 0.01 inch.

5.5 Operation of the RCP Seal Without Cooling While the RCP is in Operation

The RCP seals have been designed to survive 30 minutes of continued RCP operation with CBO on and without RCP seal cooling. The demonstration test was reported in Reference 16 for the BJ-SU seal (See Section 7). No seal failure occurred; however, increased CBO flow was noted. This increased leakage can not be attributed to pop-open of one or two seal stages. Seal leakage continued increasing after cooling was restored at 30 minutes, This was most likely due to the increasing U-cup damage and heat checking of the rotating faces and heavy, uneven carbon face wear initiated during the loss of cooling event. The leakage was terminated following restoration of seal cooling,. Anecdotal evidence of the robustness of the BJ SU seals to LOSC was demonstrated during a plant event (See for example event FCS-1 in section 8). In that event the SU seal was uncooled for a period of 45 minutes while the RCP was operating; no seal leakage was noted.

A seal performance test was conducted by Sulzer on a smaller scale new generation seal design. The seal was operated at elevated temperatures (> 500 °F) for a period of 30 minutes with the RCP in continued operation[10]. No increased leakage or seal stage degradation was noted.

The manufacturer recommends that if seal cooling has been lost for more than 30 minutes, the pumps should not be restarted without station management approval. Instead, cooling should be restored as soon as possible and a plant cool down should be initiated to be followed by an outage to refurbish the seals in all pumps.

5.6 Failure of RCP Motor

Loss of CCW may also 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 component cooling water, failure of the RCP motor may occur prior to RCP seal cartridge failure. However, loss of CCW to RCPs have 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 SONGS BJ SU seal experimental test program[27]. These tests confirmed acceptable motor performance for a greater than 20 minute duration. Fort Calhoun operated their RCPs for a period of 45 minutes without CCW and did not experience a motor failure.

The recommended operating limit for the RCP motor is only a few minutes without cooling water (See Paragraph 2.3.5 of Reference 6). The motor bearings generate a large quantity of heat, which is removed from the bearings by the lubricating oil. The 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 a babbitt, which has a fairly low melting point and therefore can be damaged fairly quickly. (Babbitt is a metal lining material for the type of bearings which are used in the RCP motors.) The temperatures of the bearings are monitored by temperature sensors imbedded in the bearings.

6.0 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 2), a review of data obtained from RCP seal integrity experiments conducted by Byron Jackson (References 14, 15, 16 and 17), and Bingham-Willamette, now Sulzer pumps (Reference 10 and 18), Byron Jackson and Sulzer RCP seal operational manuals (References 19 and 21) and analytic predictions of seal performance (References 20, 21, 22 and 23).

The RCP Seal Model includes two basic models: an "Environmental Conditions" event tree (Figure 6.1-1) and an RCP seal fault trees. The Environmental Conditions event tree is common to all CE seal designs. Two fault tree models have been constructed: one for 4-stage seals (Figure 6.2-1) and one for 3-stage seals (Figure 6.2-2). The "Environmental Conditions" event tree is used to establish the value of key input parameters defining the basic events in the RCP seal failure tree.

The RCP seal failure model predicts the probability of RCP seal failure given an initiating event and a course of operator actions. Consequently the model has been developed to be sufficiently flexible to accommodate various seal designs and operating procedures. The advent of an RCP seal failure becomes in essence a complex delayed LOCA event initiator. In order to follow this event to a core damage condition additional factors must be considered associated with the availability of mitigating equipment and post-LOCA decompression. Such models are generally available in plant PSAs. Section 9 describes the selection of values for the seal parameters and Section 10 provides an example model quantification.

6.1 <u>The "Environmental Conditions" Event Tree</u>

Figure 6.1-1: RCP Seal Model Condition Event Tree

6.2 RCP Seal Failure/Leak Model (Failure Mechanisms)

Once the environmental conditions are established the conditions are transferred to an event tree to assess the potential for RCP and magnitude of seal failure. Two separate seal failure models are defined, one for a 4-stage seal and one for a 3-stage seal.

6.2.1 4-Stage Seal Model (STAGE4)

Figure 6.2-1 presents the 4-stage seal fault tree model. The 4-stage seal is common to CE plant designs prior to System 80®. Failure of 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.

6.2.2 3-Stage Seal Model (STAGE3)

6.3 Additional Considerations

6.3.1 Comments on Failures of Multiple RCPs

6.3.2 Core Damage and Core Uncovery

Figure 6.2-1: RCP Seal Failure Model (4 Stage)
Sheet 1 of 3

Figure 6.2-1: RCP Seal Failure Model (4 Stage)
Sheet 2 of 3

Figure 6.2-1: RCP Seal Failure Model (4 Stage)
Sheet 3 of 3

Figure 4.xx: RCP Seal Failure Model (3 Stage)
Sheet 1 of 2

Figure 4.xx: RCP Seal Failure Model (3 Stage)
Sheet 2 of 2

7.0 DISCUSSION OF APPLICABLE TESTS AND TEST RESULTS

Over the past 25 years considerable effort has been placed on understanding the performance of RCPs and RCP seals during accident conditions with particular emphasis on the ability of the CE PWR to cope with a loss of RCP seal cooling. These tests, which cover the range of seal designs used in CE PWRs, indicate that the hydrodynamic multi-stage seals are robust to limited duration LOSC events. This section summarizes the key elements of those test programs and presents important test results.

In all, six test programs are discussed. These test programs have been conceptually divided into the following three categories:

1. Loss of Seal Cooling with RCP Operating

   RCP seal performance tests investigating the RCP seal heatup leakage following a limited duration Simulated Loss of Seal Cooling with operating RCPs. Tests are conducted at nominal RCS operating conditions. Typically these events look at RCP operation for a period of about 30 minutes.

2. RCP seal performance following Loss of Seal Cooling for Static RCPs

   These tests investigate the response of the RCP during transient events in which the cooling water in lost to the RCP seals and the RCP is expected to be tripped. Such events include SBO and LOCCW events when operating procedures are followed. Static RCP tests are intended to demonstrate the robustness of the seals to a long duration high temperature, high pressure exposures. Exposure intervals vary from about 8 hours to more than 50 hours.

3. Elastomer Performance Experiments

   These tests are specifically designed to understand the degradation mechanisms associated with RCP seal elastomers. They do not provide direct confirmation of seal operability, but they do provide confidence that seal materials are capable of withstanding a locally harsh environment for extended time periods.

These experiments are discussed in the following Sections.

7.1 <u>Tests of Loss of Seal Cooling with RCP Operating</u>

Two tests are included in this category. These include one BJ SU seal design confirmation test and one Bingham-Willamette test on a smaller scale RCP seal.

7.1.1 Byron Jackson Loss of CCW Test for San Onofre

The purpose of this test was to demonstrate that following a LOCCW the RCP seal cartridge would remain operable and not leak following the restoration of CCW. Specifically this test was intended to demonstrate that a 30 minute LOCCW incident would not cause a rapid deterioration of the pump shaft rotary seals, static elastomer seals, stationary and rotating metal seal cartridge components or cause the pump to seize.

A loss of CCW test was run on one of the primary reactor coolant pumps built for Combustion Engineering for installation at San Onofre Nuclear generating Station. Once the pump was operating cooling to the seals was terminated. The maximum duration of the test was determined to be 30 minutes. CBO was not isolated and the RCP continued to run. At the conclusion of 30 minutes, CCW was gradually restored. The peak temperature of 532 °F was recorded in the second stage seal cavity.

The RCP and associated seals performed well during the test. During the LOCCW the CBO was limited to 1.85 gpm and a seal bypass flow of 0.26 gpm was noted. Post examination indicated damage to the Nitrile U-cup, a broken vapor seal rotating face, heat checking on the rotating faces, some out of specification seal part cartridge dimensions and a slight loss of fit. Based on post test examination, it was noted that the seal cartridge elastomers, and the rotating U-cup seals in particular, appeared to be the parts most subject to deterioration and the main contributors to the observed above normal leakage. The U-cups are considered particularly susceptible to high temperature deterioration as they are made of Nitrile rubber and have a specified operating temperature limit of 250 °F. O-rings are constructed from ethylene - propylene and have a maximum specified operating limit of 350 °F. Only the lowest seal cartridge O-ring showed any noticeable indication of incipient U-cup extrusion.

As CBO was operational, the seal temperatures in all stages increased rapidly. The lower three stages indicated similar heatup with temperatures of all three stages exceeding 500 °F. During the 30 minute LOCCW test the vapor stage peak temperature reached about 400 °F. Vapor stage temperatures were lower as this last stage is subject to greater ambient heat loss and lower pressures.

It was noted that 24 minutes into the test the maximum seal bleedoff increased from 0.92 gpm to 1.8 gpm. The seal leakage at the same time increased from essentially zero to 0.26 gpm. Following the test the seal leakage remained at about 0.4 gpm. Seal leakage continued to rise to a peak value of 0.51 gpm.

Post-test inspection showed some deterioration of the elastomers and a cracked vapor seal rotating ring. The lockring retained the pieces of the cracked vapor seal, which maintained satisfactory sealing. This test confirmed the capability of the seals to withstand an abnormal event equal to or more severe than a SBO.

7.1.2 SCE Loss of Cooling Test Bingham-Willamette-Los Alamitos Test

Bingham-Willamette Company, in cooperation with Southern California Edison, subjected a 4.5 inch diameter seal (4-stage) to a series of tests to demonstrate acceptable seal performance for 30 minutes following the loss of seal cooling. In this test, the roughly 1/2 scale seal assembly was tested on an operating pump at station blackout conditions. SCE used their Alamitos Generating Station, Unit 3. The test results showed stable behavior. The seal did not exhibit unstable behavior any time during the test and there was no discernable increase in leakage.

Considerable data on seal performance during a loss of cooling event was gained from the test performed on December 19, 1978 at Byron Jackson using a SONGS reactor coolant pump with a BJ SU seal cartridge (Reference 11). It provides confidence in the ability of the shaft seals to withstand the effects of the loss of cooling with the pump operating. While the results of that test are not directly applicable to the Sulzer seals, the results of the test performed at Alamitos Unit 3 on Nov 1, 1985 (Reference 10)were comparable to those from the test on the SU seals. The test on the boiler circulation pump handling water at 650 °F at 2250 psi was performed on a seal cartridge utilizing improved elastomers. The smaller pump seal (4 ½" seal face vs. 9 ½" seal diameter for SONGS 2&3) was subjected to the same incoming controlled bleedoff flow temperature ramp as that which the SONGS 2&3 seals would experience during a loss of cooling event. This 30 minute test followed a period of 1 ½ hours without cooling water during which the pump seal came up on a slower ramp to an operating temperature in the 450 °F to 500 °F range.

The 4½" seal test is considered applicable to the large SONGS seals since the smaller seal has lower thermal capacitance, which causes the seal to heatup more rapidly than the 9½" RCP seal. Therefore, the resultant thermal environment would be more severe. The reduced time at high temperature in the full-size seal provides additional conservatism in applying the 4 ½" circulating pump seal test results to the larger RCP seal, since seal failure is usually associated with exposure of the elastomers to high temperature over an extended time and to increased rubbing engagement of the seal faces at the higher temperature as fluid viscosity is reduced. It should be noted that there was no significant change in seal leakage during the test.

The pump seal cartridge was disassembled following the test to establish the seal condition following the event. The overall condition of the seal, considering the elevated temperature exposure, was excellent. Minor damage was noted in one O-ring in the vapor seal.

The test results from Reference 10 and the analysis in the O'Donnell report, Reference 18, demonstrate that the Sulzer seals can operate for thirty minutes without cooling water to the seal cooling heat exchanger without significant damage or increase in seal leakage. The examination of the 4 ½" seal following a thirty minute loss of cooling test showed that the seal was in such a good condition that it could have continued to operate without cooling for an additional extended time(12).

7.2 Tests of RCP Seal Performance Following Loss of Seal Cooling for Static RCPs

Seal cooling and power to the RCPs will be lost simultaneously during Station Blackout conditions. This accident condition was investigated in seal test programs. These tests included a 50+ hour SBO simulation on the BJ/SU seal design, and an 8 hour SBO simulation on the N-9000 seal. These tests are described below.

7.2.1 Byron Jackson Loss of CCW Test for St. Lucie

The purpose of the Reference 15 test was to demonstrate and evaluate the integrity of the RCP seal cartridge under extended conditions of hot shutdown with cooling water secured and the RCP stopped. These conditions were an attempt to simulate the pump performance during station blackout conditions as understood at that time.

The seal cartridge was tested in a water loop heated to 550 °F and pressurized to 2250 psig. Controlled bleedoff was not isolated. The loss of component cooling water test was performed on the RCP seal cartridge during a hot standby condition. The test lasted 100 hours. The maximum seal leakage that occurred during the test was 16.1 gph which was considerably under the 40 gpm maximum allowed by the test procedure.

A maximum lower seal temperature of 516 °F occurred about 3 hours before the cooldown of the test fixture. The seal pressure readings at this point indicated that the seals were still staging properly; 2290 psig - lower seal, 1795 psig - middle seal, 1050 psig - upper seal and 590 psig - vapor seal. The high vapor seal pressure at the end of this test suggests a partial degradation of the third seal stage. The integrity of the remaining stages maintained controlled bleedoff low. The controlled bleed-off flow was considered good under these conditions, fluctuating between 0.5 and 0.8 gpm. Complete seal failure never occurred on any seal stage during this test.

The pressure readings in each seal cavity indicates that all seals were retaining flow normally during most of the test. The upper seal was not completely sealing between 5 and 22 hours (the pressure readings between 500 and 600 psi from the chart should have been between 800 and 900 psi). Pressure dropped briefly at 30 hours and again between 33 and 45 hours. The lower seal was leaking slightly at 28 hours and again during test cool down between 58 and 60 hours.

Observations indicate that while no stage failed some seal degradation was noted as the event progressed:

- Upper seal was not completely sealing between 5 hrs and 22 hrs.
- Seal leakage on the order of 0.25 gpm was noticed at sporadic intervals.
- Unstable CBO flow was noted indicating the potential for temporary opening and closing of seal gaps.

Based on the results of this test it was noted that sustained seal water temperatures > 250 °F will cause the U-cups to become permanently hard. Similarly, sustained temperatures in excess of 350 °F will cause the O-rings in the seal cartridge to extrude from their grooves and to become permanently distorted.

The seal cartridge was disassembled and inspected after the test and all pressure containing housings and the seal sleeves were still within the drawing tolerances. The seal damage included a broken vapor seal rotating face ring, permanent compression of all O-rings, permanent hardening of all U-cups, slight out-of-round condition of the U-cup followers and the spring holders, and slight distortion of all lapped surfaces. The Nitril U-cups are used to maintain design contact pressure between the rotating and stationary seal faces.

O-ring extrusion of the back-up ring seat gasket was evident in both the lower and upper mechanical seals during post test inspection. This O-ring extrusion was most likely due to the high temperature effects under pressure on the O-rings and together with the Nitril U-cup degradation may account for the occasional leaking of both of these seals during the test. The high water temperature in the vapor seal cavity and its leakage across the seal to the low pressure collection chamber can account for the fracture of the vapor seal rotating face ring. This unstable condition of water flashing to steam created a shock loading on the rotating face which was enough to crack the ring. A similar occurrence was observed during another loss of cooling water test, with the RCP operating, which also fractured the vapor seal rotating face. The fluid in the vapor cavity appeared to be a saturated steam water mixture with temperatures in the vapor seal cavity exceeding 400 °F. Slight leakage was observed at the bolted joint between the seal cartridge and the test fixture at the 36-1/2 hour of the test, but it soon stopped. No more leakage was detected in this area for the remainder of the test. This leakage was not attributed to seal failure, but rather was attributed to conditions associated with the testing apparatus.

7.2.2 Byron Jackson N-9000 SBO Test

Byron Jackson Pump division contracted with Combustion Engineering, Inc. to perform a simulated Loss of CCW Test, Reference 17, on an aged type N-9000 pump seal cartridge. The test provided information on the dynamic performance of an N-9000 seal under accident conditions. The test was designed to simulate a worst-case event station blackout. The test included a limited system decompression and re-pressurization including the impact of shaft motions. The N-9000 seal investigated included three stages. The forth stage (or vapor stage) is optional, however it is used in all CE PWRs. The N-9000 seals differ in many details from the earlier BJ seal designs. One specific item of note is the exclusive use of ethylene-propylene compounds for all the seal elastomers.

The RCP seal test was conducted in at the Combustion Engineering Laboratory. Initial test conditions were 555 °F and 2200 psig. This is representative of maximum hot standby conditions for most CE PWRs. The test schematic is presented in Figure 7.2-1. The RCP shaft motion and RCP seal pressures simulated the response of the plant to a Station Blackout event. The initial shaft position was set at 0.114 inches.

Including a pre-heat period, CBO was maintained for the first 1.5 hours. The complete test lasted 8 hours. At the conclusion of the test CBO was restored and the system was depressurized. During the test measurements were made of the seal cavity pressures, temperatures, CBO and seal leakage and shaft displacement. A detailed inspection was performed on the seal assembly following the test.

The test consisted of the response of an N-9000 RCP seal to a bounding loss of seal cooling transient incorporating elements of a SBO followed by a system decompression and re-pressurization due to an interruption of natural circulation. CBO was used to heat up the RCP seals. During the initial phase of testing the lower and middle seal temperatures reached and maintained temperatures in excess of 500 °F. The lower seal experienced the greater temperature. The upper stage temperatures, as measured by the CBO bleedoff was in the vicinity of 300 °F. The temperature drop was indicative of ambient heat losses. CBO staging pressures were within expected limits, indicating the integrity of the seal stages.

About 1.5 hours into the test (this was also identified as 0.5 hours after the lower seal reached the desired initial condition) the CBO flow was isolated. As expected isolating the CBO line propagated the lower stage pressures to all the stages. Since hot water was no longer being transported to the upper stages, the temperature at the various RCP seal cavities dropped. After holding a constant RCP pressure of 2200 psia for approximately 3 hours, the RCP fluid pressure was reduced to 1688 psig. Simultaneously the RCP shaft displacement was reduced to 0.072 (inches), a net motion of 42 mils. This condition was maintained for a period of 2.5 hours. The RCP seal fluid was then pressurized to 2400 psig. One secondary O-ring in the upper seal failed approximately 8 hours into the transient, causing a stage leakage through a radially drilled hole in the carbon seal face. The leak created a small bypass flow which connected to the CBO pathway. The resulting flow caused a re-staging of the seal cavity pressures.

A detailed model of the RCP seal components was developed by B-J to assess the N-9000 seal failure. The model considered seal and clearance dimensions, seal temperatures, and hydraulic loadings to establish the likelihood of material extrusion to estimate the seal material thermal transient and associated component exposures. This study identified that the weakest link in the seal was a stationary O-ring in the last stage. Failure of this O-ring was predicted to expose a small flow hole in the seal face to a pressure difference which would create a bypass pathway. During the test, this failure occurred as predicted. The flow rate through this path was roughly equal to the CBO flow.

7.3 RCP Seal Elastomer Experiments

The previous experiments provide considerable information regarding the capability of RCP seal component elastomers to survive exposure to high temperature environments. Most of these tests involve geometry-independent performance characteristics. One test specifically investigated the SONGS seal arrangement, and is described below.

7.3.1 O-Ring Static Seal Performance Under LOCCW to RCP

The primary objective of the Reference 13 test program 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 Loss of Component Cooling. 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 2250 psig nominal pressure. Each test included two different size seals and backup ring. Each of the O-ring seal was subjected to three temperature environments: 550 °F, 600 °F and 650 °F. In addition, seal "hardness" measurements were also performed on 1 inch segments of the seals.

<u>Test Results for 550 °F Elastomer Exposure</u>

During this test the seals in the facility were exposed to 550 °F environment for eight hours. This exposure level is typical of the bounding hot standby RCS temperature. Both seals tested in the facility functioned satisfactorily for the entire time period without any measurable leakage. The seals did not exhibit signs of gumminess or embrittlement. Extrusion into gap clearances was minimal. A small decrease in seal hardness (between 2 and 16 %) was noted.

<u>Test Results for 600 °F Elastomer Exposure</u>

During this test the seals in the facility were exposed to 600 °F environment for eight hours. Both seals tested in the facility functioned satisfactorily for the entire time period without any measurable leakage. The seals did not exhibit signs of gumminess or embrittlement. A decrease in seal hardness (between 16 and 28 %) was noted. Further, 60% of the backup ring material had extruded into the clearance gap. During the last 4 hours of the test a slight but noticeable drop in seal pressure across one of the seals was noted. This drop was attributed to volume expansion of the seal cavity due to O-ring extrusion.

<u>Test Results for 650 °F Elastomer Exposure</u>

During this test the seals in the facility were exposed to 650 °F environment until seal failure was observed. One of the two elastomer O-rings failed at 1 hour and 18 minutes into the heatup (this was approximately 2.5 hours after the seal temperature reached 500 °F. The second seal failed after 4 hours and 16 minutes (approximately 5.5 hours after the seal temperature reached 500 °F. Disassembly indicated severe material breakdown. Elasticity of the seals was completely lost and stretching the seal caused permanent distortion.

8.0 LOSS OF SEAL COOLING EVENTS AT OPERATING PLANTS

Operating events at nuclear plants has provided additional evidence for the robustness of the multistage RCP seal used by CE PWRs. Over the pass twenty five years, twenty one total Loss of RCP Seal Cooling events have occurred at CE PWRs. Most of these events occurred in the early years of plant operation. The Loss of Seal Cooling events varied in duration from very short (under 10 minutes) to greater than 4 hours. Several events included extended RCP operation. However, no LOSC event that occurred at a CE plant has resulted in failure of a single seal cartridge. This section assembles and summarizes the significant LOSC events at CE plants since 1974. The event data is presented in Table 8-1 and is arranged first by plant, and then chronologically. The information contained in Table 8-1 includes:

Plant Name/Event ID:	A unique event identifier to allow event to be readily referenced in Section 9, and consistent with earlier versions of CEOG RCP Seal reports
Date of the event	
Type of RCP seal:	To date, LOSC challenges have occurred only for BJ/SU and KSB RCP seal designs
Event category:	SBO, LOCCW or LOCCW/Loss of Safety Injection
Duration of event	The duration of concern is the time interval from the initial loss of seal cooling to seal cooling restoration.
Description of the event	Information was extracted from several sources including event LERs, staff interviews, utility internal reports and other related information notices.
Status of Controlled Bleedoff (CBO)	Established based on direct reports, procedural expectations or review of cavity pressure data.

Table 8-1
CE Plant Operating Events Leading to Loss of RCP Seal Cooling

Plant Name	Date of Event	Event No.	RCP Seal Type	Event Category	Duration (hrs)	CBO Isolated?	Event Description
Arkansas 2	6/24/80	ANO2-1	BJ SU	SBO	0.1	No	Partial loss of AC power, One vapor seal leaked (1.5 - 2 gpm) and was replaced.
Arkansas 2	6/3/88	ANO2-2	BJ SU	LOCCW	0.6	No	Degraded CCW flow to all four RCPs for 35 minutes. Corrective action was to vent the CCW pumps and restore flow. No Leakage or failure observed.
Fort Calhoun	4/17/74	FCS-1	BJ SU	LOCCW	0.75	No	CCW inadvertently isolated CCW to RCPs on ESFAS. 4 RCPs operated for 45 minutes without cooling. (RCS cold leg temperature peaked at 544 deg F). No failure occurred.
Fort Calhoun	9/20/75	FCS-2	BJ SU	LOCCW	Unknown	No	Loss of CCW to all four RCPs resulted on one failed stage on one pump. Seals changed in all four pumps after incident.
Fort Calhoun	xx/xx/81	FCS-3	BJ SU	LOCCW	1	No	CCW lost for 1 hr while plant was in hot standby. Plant was in hot standby 1 hr after LOCCW. Pumps restarted normally. No seal degradation.
Fort Calhoun	7/1/92	FCS-5	BJ SU	LOCCW	0.1	No	CCW flow lost to pump during startup. RCP operated for 5 minutes while seal temperature increased. RCP and seals operated for the rest of the cycle with no problems.
Fort Calhoun	7/xx/92	FCS-6	BJ SU	LOCCW	0.1	No	Same as FCS-5.
Millstone 2	11/15/84	MNS2-1	BJ SU	LOCCW	4 →9	No	On November 15, the P-40D pump was secured and CCW isolated to replace an identical leaking 3" s.s. flex hose. The lower seal temperature increased. After the repairs, CCW was re-established, and the pump was restarted four hours later. The pump was secured again due to high vibration readings, which was later determined to result from an instrumentation malfunction. The pump was again restarted on November 16, and pressure indications revealed no immediate damage to the seals. Seals properly operated for next two months. No stage failure observed. Plant maintained at hot standby.

Table 8-1
CE Plant Operating Events Leading to Loss of RCP Seal Cooling

Plant Name	Date of Event	Event No.	RCP Seal Type	Event Category	Duration (hrs)	CBO Isolated?	Event Description
Millstone 2	11/16/84	MNS2-2	BJ SU	LOCCW	3-6 hrs	No	On November 16, while on hot standby (RCS ~530 °F), Operation secured P-40B-RCP. RBCCW was then isolated to this pump for maintenance to replace a leaking 3" s.s. flex hose. As a result, the RCP seal assembly lost cooling capability, and seal temperature began to increase rapidly. When the pump was restarted about 6 hours later, pressure on the middle seal was 2,200 psig (normal is 1,475 psig), indicating a lower stage failure. The upper seal pressure was fluctuating between 950 to 1,350 psig (normal is 750 psig), indicating middle stage degradation. [ ]
Palo Verde 2	4/4/86	PV2-1	KSB	LOCCW LOSI	3	Yes (after 18 min.)	Unit 2 RCP 2B experienced a condition similar to an SBO due to a localized flow blockage. Seal injection and seal recirculation was interrupted for three hours. RCP operated for 10 minutes prior to trip. CBO unisolated for 18 minutes. Seal performance degraded but functional following conclusion of event and the affected RCP was placed back into operation. When operating at hot standby, automatic actuation to all 4 channels of RPS occur due to low RCS flow. The cause is the outlet of the high pressure cooler being restricted. The filter was flushed, RCP 2B restarted at 3 hr and the RPS was reset at 4.7 hrs.
Palo Verde 2	7/1/86	PV2-2	KSB	LOCCW LOSI	Unknown	N/A	While operating mode 1 (power operation) at 30% reactor power, leakage was determined in the RCS from the RCP 2B seals. Plant was Shutdown/Cooldown to replace all 4 RCP seals. The cause was determined to be the strainer flushing techniques employed at the time. The CBO was unisolated for 18 minutes. Failure was attributed to degradation incurred following the April 1986 incident on RCP 2B.

Table 8-1
CE Plant Operating Events Leading to Loss of RCP Seal Cooling

Plant Name	Date of Event	Event No.	RCP Seal Type	Event Category	Duration (hrs)	CBO Isolated?	Event Description
Palo Verde 3	3/3/89	PV3-1	KSB	LOCCW/ LOSI	1.2	No	LOSP resulted in a simultaneous loss of seal injection and CWW cooling. Conditions lasted for 90 minutes. Third stage temperatures estimated to have reached 437 °F. Vapor seal leakage reached 1.25 gpm, indicative of CBO flow directed to containment All RCP seals were replaced. [ ]
Palo Verde 1	11/21/83	PV1-T	KSB	Test	.6	Yes	Loss of total seal cooling at NOP/NOT conditions. CBO isolated. Peak stage three temperature < 135 F. No significant temperature transient is noticed when CBO isolated.

Table 8-1
CE Plant Operating Events Leading to Loss of RCP Seal Cooling

Plant Name	Date of Event	Event No.	RCP Seal Type	Event Category	Duration (hrs)	CBO Isolated?	Event Description
Palo Verde 1	7/6/88	PV1-1	KSB	LOCCW/ LOSI	6	Yes	Loss of partial cooling to 1 RCP for 8 hrs. Seal temperatures reached 152°F. The loss was caused by an auxiliary transformer loop transient. No seal failure occurred. [ ]
St. Lucie 1	4/15/77	SL1-1	BJ SU	LOCCW	Unknown	No	Loss of containment instrument air resulted in Loss of CWW to RCP Seals of St. Lucie Unit 1. All seals were replaced.
St. Lucie 1	6/11/80	SL1-2	BJ SU	LOCCW	1.5	No	Operating at full power, Loss of CCW lasted 1.5 hrs, but plant was placed on shutdown cooling for 8 hrs. No leakage or degrations are noted; all seals were replaced.
St. Lucie 2	8/26/80	SL2-T	BJ SU	SBO	>50	No	Loss of all AC Power and no CCW. Shows that there is no significant seal failure during the test except for an abnormally high vapor seal temperature and pressure. Post inspection showed cracked vapor seal rotating rings, deformation of the o-rings and hardening of the U-cups. The test confirms that the seals can withstand SBO for an extensive time.
St. Lucie 2	12/19/84	SL2-2	BJ SU	LOCCW	0.5	No	Pumps 2B1 and 2B2 seals failed due to loss of CCW caused by loss of power to CCW valves. No stage failure observed. Plant maintained at hot standby. Seals were replaced.
St. Lucie 2	8/8/85	SL2-3A SL2-3B	BJ SU	LOCCW	4.5 0.23	No	An inadvertent ESF actuation coupled with a design flaw resulted in loss of cooling to 2 of the four RCP seals for 4.5 hours. Third Stage of two RCP seals degraded, possibly failed.
SONGS2	3/xx/83	SOS2-A	BJ SU		0.5-0.75	No	CCW was secured for the event. No seals failed but were replaced due to concern with exposure of elastomers to elevated temperature.
SONGS2	12/19/78	SOS2-T	BJ SU	LOCCW	0.5	No	Pump ran 30 minutes without CCW to RCP seal. Ran for 2.5 hours after CCW restored to the seal and seal leakage rates return to normal. Post-test inspection shows cracked vapor seal rotating ring and some deterioration of the elastomers. Seal leakage never exceeded 3 gpm. Found 2 gpm (controlled leakage) and 0.5 gpm (vapor seal leakage)

Table 8-1
CE Plant Operating Events Leading to Loss of RCP Seal Cooling

Plant Name	Date of Event	Event No.	RCP Seal Type	Event Category	Duration (hrs)	CBO Isolated?	Event Description
Waterford 3	2/20/85	WSES3-1B	B-J	LOCCW	0.67	No	Upon receiving a containment spray actuation signal. The CCW Containment Isolation Valves (CIVs) closed, securing cooling water flow to the RCP seal coolers. A pressure surge within the CCW piping during the containment isolation caused the RCP seal cooler isolation valves for 3 of the 4 RCPs to close. The 3 affected RCPs were secured since seal cooling could not be restored within the required 3-minute time limit. The fourth pump was not secured since cooling water was restored when the CCW CIVs were reopened. After about 40 minutes, one of the secured RCPs had heated up to the point where stage pop-open likely occurred. Approximately a 3-GPM leak to atmosphere was observed from the upper seal. A plant cooldown was initiated at this point. The seals in the 3 affected RCPs were replaced. The RCPs were manufactured by Byron Jackson. Testing has demonstrated that a loss of CCW for 30 minutes with the RCP operating and for much longer periods with the pump secured has not resulted in failure of the seal to maintain system pressure. However, degradation of the seal cartridge as evidenced by improper seal stage pressure breakdown can occur in a relatively short time following interruption of CCW flow to the seal coolers. 3 RCP seals exposed to loss of CCW for 4.5 hours (see below) Plant maintained at hot standby. One seal stage failed. All the seals affected were replaced.
Waterford 3	2/20/85	WSES3-1A	B-J	LOCCW	4.5	No	Same event as above

9.0 QUANTIFICATION OF THE RCP SEAL FAILURE MODEL

This section provides the basis for quantification of the CEOG seal failure models presented in Section 6.0. 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, to some extent, seal design specific. The current quantification does not address the selection of plant operational parameters associated with the onset of LOSC events and associated post-accident actions. These parameters are plant specific. 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 an RCP seal LOCA.

9.1 General Approach To Model Quantification

9.1.1 Summary of Loss of Seal Cooling Test Data and Operational Occurrences

Table 9.1-1
Summary of Loss of RCP Seal Cooling Events and Experiments

Plant	Date	Event No	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Arkansas	6/24/80	ANO2-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Arkansas	6/3/88	ANO2-2	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
FCS	4/17/74	FCS-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
FCS	9/20/75	FCS-2	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
FCS	1981	FCS-3	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
FCS	7/1/92	FCS-5	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
FCS	7/92	FCS-6	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
MP2	11/15/84	MNS2-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
MP2	11/15/84	MNS2-2	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
PV1	11/21/83	PV1-T	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
PV1	7/6/88	PV1-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
PV2	4/4/86	PV2-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
PV2	7/1/86	PV2-2	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
PV3	3/1/89	PV3-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SL1	4/15/77	SL1-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SL1	6/11/80	SL1-2	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SL2	8/26/80	SL2-T	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SL2	12/19/84	SL2-2	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SL2	8/8/85	SL2-3A	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SL2	8/8/85	SL2-3B	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SONGS2	3/83	SOS2-A	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SONGS2	12/19/78	SOS-T	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
WSES3	2/20/85	WSES3-1A	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
WSES3	2/20/85	WSES3-1B	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
Bingham	12/87	BINGT-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
BJ N9000	10/15/79	BJT-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
SONGS		ELAS-1	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

Notes on Table 9.1-1

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9.2 Quantification of Seal Failure Parameters

9.2.1 RCP Stage Failure due to Elastomer Degradation [ ]

Table 9.2-1
Elastomer Failure Probability Calculation

Figure 9.2-1
Probability of Elastomer Induced RCP Seal Failure

9.2.2 Random Failure Probability [ ]

Table 9.2-2 summarizes the RCP failure contribution to random RCP failure probabilities.

Table 9.2-2 Random RCP Seal Stage Failure Probability				
Exposure Time	**< 1 hr**	**1hr < T < 2 hrs**	**2 hrs < T < 4 hrs**	**T > 4 hrs**
Representative CE PWR	[ ]	[ ]	[ ]	[ ]
PVNGS	[ ]	[ ]	[ ]	[ ]

9.2.3 Hydraulic Instability/Pop-Open and Stage Failure [ ]

Table 9.2-4
RCP Seal POP-OPEN Failure Probability Calculation

Figure 9.2-2
Probability of "Pop-Open" RCP Seal Failures

9.2.4 Common Cause Relationships

9.2.5 Comments on the Treatment of a Pre-Existing Failure [ ]

9.3 Quantification of the Event Tree and Fault Tree Models

Table 9.3-1
RCP Fault Tree Basic Event Probabilities for SU 4-Stage Seal Design

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Table 9.3-2
RCP Fault Tree Basic Event Probabilities for Improved 4-Stage Seal Designs

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Table 9.3-3
RCP Fault Tree Basic Event Probabilities for 3-Stage Seal Design

	[ ]				[ ]				[ ]				[ ]			
	[ ]				[ ]				[ ]				[ ]			
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Table 9.3-4
Conditional RCP Seal Failure Probability for Various CE PWR Seal Designs

9.4 Sensitivity Studies

Table 9.4-1
Comparison of Conditional Failure Probabilities

10.0 IMPLEMENTATION OF RCP SEAL MODEL: SAMPLE CASES

Section 9 established the conditional failure probability for an RCP seal given an LOSC initiating event, followed by subsequent operator actions. The typical end state established through this methodology is in essence a delayed loss of inventory initiating event. This section provides example calculations which show how the conditional RCP seal failure probabilities are incorporated in typical LOSC event sequences of concern. Values used in this calculation are approximate and for purposes of illustration only. They are not specifically applicable to any one PSA but are generally representative of PSA data for the CEOG member plants.

The calculations presented in the following sections represent the: (1) probability of a station blackout with a subsequent RCP seal induced small LOCA and (2) the probability of a loss of CCW event that results in an RCP seal induced small LOCA. The calculation is performed for three seal designs: BJ-SU, BJ-N-9000 (4 stage), and Sulzer three stage.

10.1 Sample Case 1: Station Blackout Induced RCP Seal LOCA

This section estimates the probability of a station blackout induced RCP seal LOCA. The calculation assumes a LOOP event followed by failure of both EDGs (no AAC capability is assumed). The turbine driven AFW pump is assumed available as is battery power .

Based on the forgoing assumptions and using data from Reference 25 we have:

$P_{LOOP} = 0.04$ / year
$P_{EDG\_FTS} = 0.02$ /demand
Common Cause EDG failure probability = 0.025
$P_{NON\_RECOVER} = 0.4$ (at 4 hours)

During an SBO the RCP is tripped. [The most limiting condition is when CBO is not isolated and the RCS subcooling margin is not maintained greater than 50 °F.]

Frequency of a 4 hour SBO = $0.04 \times (.02 \times .02 + .02 \times 0.025) \times 0.4 = 1.4 \times 10^{-5}$ / yr

The resulting probability of this event propagating into a small LOCA is summarized in Table 10.1-1. In establishing the probability of a loss of coolant event the conditional probability of RCP failure obtained from Section 9 is multiplied by four to reflect the exposure of 4 RCPs to a familiar degrading environment.

Table 10.1-1 **Frequency of SBO Induced Seal LOCA**		
Seal Type	**Conditional Failure Probability (per pump)**	**Event Frequency (per year)**
BJ SU	[ ]	[ ]
BJ-N-9000	[ ]	[ ]
3 Stage Sulzer	[ ]	[ ]

The above calculation is approximate and likely overestimates the impact of seal failure. The actual impact of this event on core damage frequency will be plant specific and would require integration of results of this model into the plant specific PSA.

10.2 Sample Case 2: RCP Seal LOCA Induced By LOCCW

This section estimates the probability of a RCP seal LOCA induced by a LOCCW event. This event differs from the SBO in that power is available to mitigate LOCA should one develop. The calculation assumes that a LOCCW occurs. The operator is assumed to follow procedures which result in tripping the affected RCPs. The plant may or may not isolate CBO. [ ]

The following values are representative of this scenario:

$P_{LOCCW} = 0.05$ / year
$P_{OP\_TRIPS\_RCPs} = 1.0$
[ ]

The resulting probability of this event propagating into a small LOCA is calculated by multiplying the above probabilities by the conditional RCP seal probability. These results are summarized in Table 10.2-1 and 10.2-2.

Table 10.2-1 **Frequency of LOCCW Induced Seal LOCA** [ ]		
Seal Type	**Conditional Failure Probability (per pump)**	**Event Frequency (per year)**
BJ SU	[ ]	[ ]
BJ-N-9000	[ ]	[ ]
3 Stage Sulzer	[ ]	[ ]

Table 10.2-2 **Frequency of LOCCW Induced Seal LOCA** [ ]		
Seal Type	**Conditional Failure Probability (per pump)**	**Event Frequency (per year)**
BJ SU	[ ]	[ ]
BJ-N-9000	[ ]	[ ]
3 Stage Sulzer	[ ]	[ ]

Since plant resources are available to respond to the event, the impact of these failures on plant core damage frequency should be negligible provided there is no common cause CCWS dependency that also fails safety injection.

11.0 SUMMARY AND CONCLUSIONS

This report presents a mechanistically based probabilistic model for the failure of the multi-stage hydrodynamic seals used in CE designed PWRs. The model considers failure mechanisms associated with elastomer degradation and seal hydraulic instability. Values for PSA model parameters were based on data obtained from RCP seal testing, loss of seal cooling events at operating PWRs and extrapolations to accommodate the impact of seal design improvements on the failure probability of improved RCP seal designs

Results of this assessment indicate that the conditional probability of a RCP seal LOCA is negligible for short duration loss of cooling events, [ ]. It was also noted that the RCP seal failure probability is negligible for CE PWRs with the improved RCP seal designs. The specific impact of RCP seal failure on plant core damage probability is plant specific and is affected by plant and seal design, and plant procedures governing post-accident cooldown.

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APPENDIX A

Summary Descriptions of RCP Seal Designs Used By CE Plants

APPENDIX A
TABLE OF CONTENTS

Description **Page**

LIST OF FIGURES

A.1 Seal Cooling

Component cooling water is the source of cooling for the pump seals. The normal cooling water flow rate to each seal cooling heat exchanger is 35 gpm for BJ RCPs. The CE RCPs at PVNGS require 75 gpm per pump for the high pressure cooler and 17 gpm for the interstage seal cooler. The flow rate is typically not available to the plant operator, since it is typical that only a low flow switch provides alarm functions to either the plant computer or control room annunciator, or both. Both the temperature and the flow rate of this cooling water may vary significantly depending upon plant system configurations. It is also appropriate to note that the component cooling water system provides cooling to the RCP motor. This factor becomes important when considering appropriate operator actions during a loss of cooling water. There are certain distinct differences in the configuration of the seal cooling heat exchangers installed on the RCPs.

A.1.1 Tube–In-Shell Seal Cooling Heat Exchanger Design

At Palisades and Ft. Calhoun the seal cooling heat exchanger is in a tube-in-shell configuration in a parallel path to the CBO flow from the RCS to the seal cartridge and external to the pump case. The total flow of component cooling water flows in parallel through the shell of the tube-in-shell heat exchanger and through an internal cooling jacket in the pump cover. The internal cooling jacket, also called the thermal barrier, is located immediately below the pump recirculating impeller and just above the hydrostatic bearing. There is a relatively small clearance between the pump shaft and the pump cover in this internal cooling jacket region. The internal cooling jacket, which is a drilled hole heat exchanger, provides significant cooling at all times while cooling water flow is available - whether the pump is running or idle. However, flow through the high pressure primary side, the tube, of the tube-in-shell heat exchanger is provided by the recirculating impeller that is driven by the pump shaft. The recirculating impeller is located directly below the seal cartridge and provides a recirculation flow rate of approximately 40 gpm through the external heat exchanger. This cools the hot RCS fluid before it enters the first stage of the seal cartridge. In other words, hot RCS fluid at a rate of 1 gpm flows upward through the annulus between the pump shaft and the pump cover. It mixes with the 40 gpm being recirculated by the recirculating impeller, while cooled fluid enters the seal cartridge at a rate of 1 gpm. The external heat exchanger provides greatly reduced cooling to the CBO flow when the pump is idle. Thus high temperature alarms may be activated at any idle RCP when the RCS is hot.

A.1.2 Tube-In-Tube Seal Cooling Heat Exchanger Design

At Arkansas 2, Millstone and St. Lucie 1 & 2 the seal cooling heat exchanger is in a tube-in-tube configuration in a parallel path to the CBO flow from the RCS to the seal cartridge and external to the pump case. The total flow of component cooling water flows in parallel through the outer tube of the tube-in-tube heat exchanger and through an internal cooling jacket in the pump cover. The internal cooling jacket (thermal barrier) is located immediately below the pump recirculating impeller and just above the hydrostatic bearing.

There is a relatively small clearance between the pump shaft and the pump cover in this internal cooling jacket region. The internal cooling jacket, which is a drilled hole heat exchanger, provides significant cooling at all times while cooling water flow is available - whether the pump is running or idle. However, the recirculating impeller that is driven by the pump shaft provides flow through the high-pressure primary side tube of the tube-in-tube heat exchanger. The recirculating impeller is located directly below the seal cartridge and provides a recirculation flow rate of approximately 40 gpm through the external heat exchanger. This cools the hot RCS fluid before it enters the first stage of the seal cartridge. In other words, hot RCS fluid at a rate of 1 gpm flows upward through the annulus between the pump shaft and the pump cover. It mixes with the 40 gpm being recirculated by the recirculating impeller, while cooled fluid enters the seal cartridge at a rate of 1 gpm. The external heat exchanger provides a reduced amount of cooling to the CBO flow when the pump is idle. Thus high temperature alarms may be activated at any idle RC pump when the RCS is hot. When the pump is idle, the hot fluid comes in contact with the rotating and stationary seal faces of the first seal stage. Whether the pump is running or is idle, the CBO fluid must pass through the inner tube of the inside tube coil (which is part of the seal cooling heat exchanger) before the CBO enters the first pressure breakdown tube. Therefore a certain amount of cooling will take place, but not as much as when the recirculation impeller is running.

A.1.3 Shell-In-Shell Seal Cooling Heat Exchanger Design

At SONGS 2 & 3 and Waterford 3, the seal cooling heat exchanger is in a shell-in-shell configuration in series between the RCS and the seal cartridge and inside the pump case. The shell-in-shell seal cooling heat exchanger was developed by BJ in order to eliminate the situation where the seal cooling heat exchanger provides a reduced amount of cooling to the CBO flow when the pump is idle when the RCS is hot. An added advantage of his design is the increased heat sink in the event cooling water flow is lost. In this design the cooling water passes through a series of annular passages in the heat exchanger. The primary fluid passes at a rate of 1.5 gpm on the primary side of the heat exchanger on its way to become controlled bleedoff. This design does not require a recirculating impeller. Since the CBO fluid must pass through the heat exchanger before reaching the seals, cooling occurs whether the pump is running or idle, however, the cooling efficiency will be higher when the pump is running, due to the action of the rotating baffle.

A.1.4 High Pressure Cooler and Interstage Cooler Design

PVNGS uses a high pressure cooler and two inter-stage throttle coolers to control temperature in the RCP main shaft seal assembly.

The RCP High Pressure (HP) cooler is a shell and tube heat exchanger with seal injection water on the tube side and Nuclear Cooling water (CCW) on the shell side. The HP cooler is mounted external to the RCP motor support stand. Prior to entering the HP cooler, seal injection is mixed with recirculated water from the RCP jet pump. The water from the jet pump is driven by a feed screw on the RCP shaft. Hence, continuous water through the

HP cooler is maintained when seal injection flow from the charging pumps is stopped as long as the RCP is in operation.

Between the 1st and 2nd stage and between the 2nd and 3rd stage are two throttle coolers. These are also shell and tube heat exchangers with seal injection water on the tube side and Nuclear Cooling water (CCW) on the shell side. These coolers are mounted on the outside of the seal housing and maintain a constant temperature throughout the seal housing assembly. Small diameter tubing in these coolers drops the pressure between the seal stages instead of having the seal staging via a pressure drop orifice in the seal package.

A.1.5 Seal Face Lubrication and Use of Controlled Bleedoff

The normal operating mode of the sealing system, with one third of RCS pressure across each of the lower three stages is created by seal staging flow coils. There is a separate staging coil for each sealing stage, located in the pressure breakdown device. Each of the pressure breakdown devices is in parallel with its respective set of seal rings. The design flow rate of each coil for the Flowserve N-9000 seal design is 1 or 1.5 gpm and 1, 1.5 or 3 gpm for Sulzer seal design, depending on the plant, at a differential pressure across each coil of 750 psid. Thus each coil acts as an orifice to reduce the pressure available at each seal stage resulting in equal pressure distribution among the stages unless there is significant leakage through one or more of the stages. The second function of the coils, aside from providing seal system pressure distribution, is to permit cooling flow through the sealing system to carry away frictional heat generated by the rotating seal parts while operating at normal design conditions. Total temperature rise across the seal cartridge should not exceed 30° F, indicating good seal life and wear characteristics. During a loss of coolant event the temperature of the controlled bleedoff flow will rise rapidly, so the above described cooling function may not occur depending on the temperature of the CBO versus the temperature at the interface between the rotating and stationary faces. If the pump is still rotating, the CBO flow at subcooled conditions will provide lubrication to the seal faces.

Since the leakage flow through a given seal stage is in parallel with the staging coil for that stage, effectively bypassing the coil, cavity pressures in the seal will change as the seal leakage changes. The pressure differential across the leaking seal stage will decrease while the two non-leaking seals would equally share an increase in pressure differential (of equal magnitude to the loss of pressure differential across the leaking seal stage).

The Flowserve N-9000 and Sulzer seals are designed to operate with a thin fluid film gap. As a result, design allowances must be made for short-term contact of the seal face ring materials, particularly during low pressure pump starts. For this reason the stationary seal face ring material is resin-impregnated graphite for both seal designs. This material is also used in the currently manufactured replacement parts for the SU seals. It is also used by other manufacturers of Reactor Coolant pumps. The material for the rotating face rings in the original Byron-Jackson SU seals was titanium carbide. The material used in the N-

9000 and Sulzer seals is tungsten carbide because it has a higher fracture resistance and higher thermal conductivity (Reference A-1). All of the elastomers performing static sealing functions in both seal designs are ethylene propylene.

The Flowserve N-9000 and Sulzer RCP seals are designed to withstand all normal operating conditions that exist in the field for a minimum of 50,000 hours. Major parameters influencing the seal environment include axial shaft motions, radial shaft motions, radial shaft vibrations, temperature, pressure, and pump start/stop cycles.

A.2 Sulzer 4 Stage Shaft Seals

The Sulzer seals for SONGS and Calvert Cliffs are cartridge assemblies and are installed and removed from the pump as a unit. In the case of the Calvert Cliffs pumps, there is insufficient room to allow the entire seal cartridge to be installed and removed from the pump. Therefore the vapor stage is installed and removed separately. The seal cartridge consists of four seal stages - three stages which reduce the fluid pressure of the controlled bleedoff flow, and the fourth stage which is the vapor stage. All four stages are identical in configuration. Each of the lower three stages reduces the pressure by an equal amount, i.e., approximately 750 psi. Each seal stage, however, is designed to be capable of operating at full reactor coolant system pressure of up to 2250 psig.

Figure A.2-1 depicts a single stage of a Sulzer seal assembly.

The most important design features are described in the following paragraphs.

Stationary Seal Ring Carrier

The Stationary Seal Ring Carrier provides the necessary support and isolation for the stationary seal ring. A single anti-rotation lug located over the secondary seal prevents carrier rotation and allows the carrier to track shaft tilt without restriction. The location of the anti-rotation lug near the secondary seal which centers the carrier minimizes relative motion and wear that might otherwise occur on the mating surfaces. The backseat surface which supports the stationary ring is lapped flat within two helium light bands.

Stationary Seal Ring

The configuration of the stationary seal ring was determined by analysis and development testing. Various balance ratios, face widths, and cooling notch configurations were evaluated in the process of optimizing the design. The carbon material is strictly controlled by specifications. Non-destructive examination of the material assures internal integrity. The front and back faces are lapped flat.

Secondary Seal

The secondary seal is an ethylene propylene O-ring with a backup ring. The secondary seal assures that the pressure loading around the carrier is constant as the shaft position changes. The backup ring prevents extrusion of the O-ring in the event that a single stage is subjected to full system pressure. The procurement of the O-rings is controlled by specifications which establish the dimensions, material, inspection, and packaging. The surfaces against which the O-ring seals are coated with chrome oxide ceramic overlay which has excellent resistance to wear.

Seal Springs

The seal springs provide the necessary force for the seal to function, even with large shaft displacements. At low operating pressures the springs load provides a greater percentage of the closing force and becomes a significant part of the effective balance.

Rotating Seal Ring and Support Ring

One of the most important features of the Sulzer seal is the support concept for the rotating seal ring. During temperature and pressure transients the seal sleeve deflects at a different rate than the rotating seal ring. The rotating support ring isolates this effect so that it does not affect the rotating seal ring. This is accomplished by the similar rates of expansion of the two rings and the narrow support nose on the seal sleeve and the rotating seal ring. The location and shape of the support nose were determined by analysis to eliminate twisting moments and deflections. The rotating seal ring and the support ring are made of tungsten carbide which has good heat transfer properties and therefore does not have a tendency to heat check. Other materials which have been evaluated for this design include titanium carbide which was ruled out because of its relatively low heat transfer rate making it more susceptible to heat checking and slower to recover from temperature transients.

Seal Leakage

The Sulzer seal was designed to develop full fluid film lubrication between the rotating and the stationary seal faces while allowing a minimum amount of leakage under all credible design and off-design operating conditions. Since leakage is a cubic function of seal gap, high leakage rates can occur if the face gap is not controlled. If the gap configuration were to become diverging (instead of converging), there would be a loss of fluid film between the rotating and stationary surfaces of the seal rings resulting ultimately in seal failure. No such damage has been observed after any of the tests or any of the episodes in plants. This confirms that the seal design is capable of tolerating loss of seal cooling.

Seal Staging

Seal staging flow, which is also called controlled bleedoff (CBO), provides the pressure breakdown to distribute approximately one third of the system pressure across each of the bottom three seal stages. The CBO consists of 1.5 gpm passing through the pressure breakdown devices. These devices are small diameter tubing whose length is selected to provide the correct pressure reduction at a flow of 1.5 gpm. Another important function of the staging flow is to cool the seals.

A.3 Sulzer 3 Stage Shaft Seals

The Sulzer seals at PVNGS are very similar to the Sulzer seals used at SONGS 2 & 3 in the area of the stationary and rotating faces, carrier rings, elastomers, and seal sleeves. For this reason much of the description for the Sulzer seals for SONGS and Calvert Cliffs can be repeated here. However, the pressure breakdown devices (PBDs) are part of the pump and not part of the seal stage. The PBDs are also little interstage heat exchangers which cool the staging flow water. Since the PBDs were not replaced at the time the Sulzer seals were installed, the pressure breakdown remains at 43%, 43%, 14%, rather than the 1/3, 1/3, 1/3 used in the SONGS and Calvert Cliffs seals. The CBO which is controlled at about 3.2 gpm by the PBDs and the throttling orifice at the CBO outlet provides generous cooling to the seal faces. The interstage seal leakage between the seal faces, however, is still as low as at SONGS. PVNGS operates with seal injection, so that if CCW is lost, the seals will not be subjected to any significantly different conditions (the interstage coolers will not be performing their cooling function, but that should not result in any significant transient). The RCPs at PVNGS can operate without seal injection for an indefinite time as long as seal cooling is available.

A.4 Byron Jackson N-9000 Shaft Seals

The N-9000 RC pump shaft sealing system consists of four N-9000 mechanical seals arranged in a cartridge assembly. Because there is adequate space, the 4-stage seal cartridges at Waterford 3 and St. Lucie 1 and 2 are removed as whole assemblies. At ANO2, Millstone 2, and Palisades the three lower stages are installed into the pump and removed as a single piece cartridge unit because of space limitations between the pump shaft and the lower end of the motor shaft. They provide the primary sealing of the RC system pressure. The fourth seal, also called the vapor seal, is installed (and removed) separately. The vapor seal normally operates at low pressure to minimize outleakage from the pump. It also serves as a backup seal in the event of a failure of the lower seals. During normal pump operation, each of the three high pressure seal stages is subjected to a differential pressure of approximately one third of the RCS pressure. Each of the four individual sealing stages is designed to withstand full RCS pressure indefinitely with the RC pump idle and for a limited time with the RC pump running. Figure A.4-1 presents the cross-section of a typical 4-stage N-9000 seal assembly. Figure A.4-2 presents the cross-section of a seal assembly with three (3) N-9000 stages and an SU vapor stage such as is used at Waterford 3.

Stationary face configuration

The one-component configuration of the N-9000 stationary face uniquely avoids any hysteresis effects such as are normally encountered with two-piece designs utilizing backup rings and lapped surfaces to enhance carbon deflection conformance. The stationary face O-rings adjacent to the outer diameter and the retainer eliminate radial and hydraulic loading of the part. The stationary face "floats" on these elastometric gaskets. The holder also prevents rotation of the stationary face and maintains the axial position of the face against the springs during assembly and disassembly operations. The geometry of the stationary face has been established through finite element analysis to ensure that a fluid film is maintained at the sealing surface. The balance ratio was selected to provide low wear with optimum leak rates. The radial location of the sealing relative to the balance diameter produces a constant hydraulic loading around the face, thereby eliminating uneven facial wear should radial displacement of the shaft occur.

Stationary face gasket

Quad-rings, because of their four-lobed cross-section, have a lower stiffness than an I-ring or an O-ring of equivalent size. The lower stiffness for a given squeeze results in a lower normal force between the elastomer and the metal resulting in lower friction loads , whether dry or greased. The vent holes in the Quad-rings ensure that the pressure between the lobes is the same as the sealed pressure.

Rotating face configuration and mounting

Figure A.4-3 shows the N-9000 seal rotating assembly. The single component configuration of the rotating face eliminates any effects from frictional hysteresis which is characteristic of existing two-piece designs. The face is supported axially by the O-ring rotating face seal gasket and by fluid pressure. The geometry of the rotating face has been established through computer analysis to ensure a fluid film under all combinations of normal and transient temperatures and pressures.

The first three rotating seal faces have thermo-hydrodynamic grooves in the faces. The vapor stage rotating face does not have grooves, but there are grooves in the vapor stage stationary carbon face ring. As a result, the parts in the first 3 stages are interchangeable.

Each N-9000 seal rotating face is driven through a set of nine drive keys. Each key is made from a resilient material. They are shaped to fit into the milled slots in the rotating face drive ring and the flat surfaces on the outer diameter of the rotating face. This design eliminates stress concentrations on the face normally resulting from keyways or pin holes, and also maintains a positive drive when clearances increase as a result of increased temperatures. Driving the rotating face on its outer diameter permits a sufficiently large clearance between the rotating face bore and the outside diameter of the rotating face seat so that no interference occurs under high pressure and high temperature operating conditions, such as loss of coolant. The diameter of the rotating face bore at the rotating face seat is slightly larger than the balance diameter to provide an axial force that always seals the face against the O-ring. This diameter is not large enough, however, to unseat the rotating face under reverse operating pressure conditions.

Double spring configuration

The springs are arranged in a double spring configuration with half of the springs facing up and the other half of the springs facing down. Because the two sets of springs work in parallel, this configuration allows the use of heavier springs, larger coil separation and a low ratio of length to diameter. The result is that for any axial movement of the shaft, only half of the displacement occurs in each set of springs. The combination of the low spring rate and this spring holder arrangement permits a wide range of overall axial travel with a relatively small change in spring load. This eliminates the tendency of a single large spring to buckle.

Balance sleeve mounting

The balance sleeves are installed in the flange (upper seal) or in the pressure breakdown devices (middle and lower seals) during cartridge assembly. Pressurization results in little or no axial loading. The Quad-ring gaskets provide static sealing. A shoulder and the retaining rings maintain the axial position of the sleeve. This arrangement permits a degree of flexibility so that angular movement of the sleeve about the gasket is possible.

Elimination of unbalanced forces due to radial displacement

Radial displacement of the pump shaft does not create unequal hydraulic balance forces on the seal faces. Radial displacement of any reactor coolant pump shaft will always exist, generally as a combination of offsetting of the shaft centerline from the true pump centerline and also an orbit of the shaft about its own centerline. The N-9000 seal has been designed for a maximum horizontal (radial) shaft displacement of 0.050", which includes a shaft vibration (orbit) of 0.030" peak-to-peak (Reference A-1).

In the N-9000 seal design the carbon seal face, on which the balance diameter is machined, is stationary and is sealed to a stationary balance sleeve. Displacement of the shaft and the flat rotating seal face does not create unequal areas subject to seal differential pressures nor to unequal balance forces. Thus, unbalanced forces are eliminated from this design.

Pressure profile and lubricating film geometry

The fluid mechanical analysis used to predict seal gap behavior is a combination of the existing axisymmetric analysis and a newly developed state-of-the-art 3-dimensional analysis for the inclusion of hydropad effects. When various loadings (pressure, heat flux, elastomer and spring loads) are applied to the face, it distorts into a complex pattern involving radial and circumferential variations.

The change in circumferential direction produces a waviness, and in combination with the rotation of the carbide face, produces a hydrodynamic separating force between the sealing faces. This "hydropad" effect has been analyzed using a Flowserve proprietary computer program.

The basic sealing system descriptive information for the N-9000 seal in section A.1.5 are equally applicable to the original SU seal cartridge design. The physical parts arrangement is quite different in the N-9000 seal in comparison to the SU seal. (see Figure A.4-3). A major change in the N-9000 design is the improvement in the seal face ring deflection control. Hydrodynamic operating principles apply to both the N-900 and the original SU seal designs. However, the improvements made in deflection control for the N-9000 seal design will result in repeatable and predictable behavior with greater operating margin to tolerate transients.

A.5 Byron Jackson SU Seals

Description of Seal Cartridge

The seal cartridge uses four face-type hydrodynamic mechanical seals. The uppermost vapor seal operates at a low pressure and is specifically designed to normally operate at low pressure with negligible leakage into the containment. Primary sealing is performed by the three high pressure seals which are identical in configuration and differ only in size, diametrically increasing from the lower seal to the upper (third) seal.

As an integral part of a cartridge, tubular coils or grooved labyrinths provide a means of reducing the pressure so that each seal is subjected to only a portion of the full pump pressure.

Principles of operation

When the pump is operating, primary and dynamic sealing by each mechanical seal is achieved by a carbide rotating face running against a carbon stationary face at a calculated loading force developed by the fluid pressure and the coil springs. Additional lapped surfaces and rubber seals form the static seals.

In parallel with each high pressure seal is a tubular coil or grooved labyrinth, known as the pressure breakdown device (PBD). Each PBD is designed and manufactured with a definite cross-sectional area and length to provide a pre-determined flow for any pressure applied across it. The pressure-flow characteristics of the three PBDs are identical, so that as flow develops through each coil, the pressure drop across each seal becomes one-third of the total pressure differential across the high pressure portion of the cartridge. The flow passing through this pressure breakdown system is controlled leakage, also controlled bleedoff (CBO). A cool liquid is intentionally leaked through the seal cartridge in order to provide lubrication and cooling for the moving parts. The CBO flowrate through these seals is 1 gpm.

The inlet to the seal cartridge is subjected to pump suction pressure. If at normal operating conditions the pump suction pressure is 2150 psig, and the vapor seal cavity pressure is at 50 psig, each PBD produces a pressure drop of one-third of the total differential pressure (2100 psid), or 700 psid. Therefore the pressure below the first seal would be 2150 psig, 1450 in the second seal cavity, 750 psig in then third seal cavity, and 50 psig in the vapor seal cavity.

The leakage through a properly functioning set of seal faces is designed to be negligible – just sufficient to maintain a very thin lubricating film. If this leakage increases, the values of the seal cavity pressures would be affected. Significant seal leakage can be detected and measured only as part of the CBO. Leakage through the high-pressure seals can only be presumed and estimated from changes in the seal cavity pressures.

For hydrodynamic face-type seals to operate successfully, they must rely upon a thin film of lubrication separating the carbide rotating face from the carbon stationary face. This thin film is generated partially by a positive pressure gradient across the primary sealing gap. If the CBO discharge were to be closed (valved off), the pressure gradient across the high pressure sealing stages would become zero. This would cause the lubricating fluid film between the faces to disappear and the seals would run dry, generating excessive frictional heat and wear. At the same time the full system pressure would be across the vapor seal. Even though this stage is designed to withstand system pressure with the pump in a non-rotating condition, it is a very severe operating condition if the pump continues to operate.

Seal cooling and lubrication are accomplished by circulating the high-pressure primary coolant under the first seal through a seal cooling heat exchanger and then introducing the cooled primary fluid to into the seals. The heat exchanger uses component cooling water (CCW) to cool the primary fluid. If the CCW flow is lost, the CBO flow temperature will start to increase rapidly. The pump should be tripped as soon as possible and the CBO flow should be isolated. However, the CBO flow should never be isolated while the pump is still rotating.

The inlet to the seal cartridge is exposed to pump suction pressure. If, at full operating conditions, the suction pressure is 2150 psig and the vapor seal cavity is at 50 psig, each PBD produces a pressure drop of one-third of the total differential pressure (2100 psid) or 700 psid. The values of the observed staging pressures would be 2150 psig at the lower (#1) seal, 1450 psig in the middle (#2) seal cavity, and 750 psig in the upper (#3) seal cavity. At these pressures the flow rate through the PBDs is designed to be 1 gpm. This is the controlled bleedoff flow.

The preceding discussion assumed that the leakage across each set of seals was negligible, as significant leakage can affect the values of the seal cavity pressures. Seal leakage can be detected and measured as a direct output only from the vapor seal. Leakage from the high pressure seals can only be presumed and estimated from changes in the seal cavity pressures.

Deviations in seal cavity pressure can occur not only from seal leakage, but also from changes in characteristics of the pressure breakdown devices (PBD). These changes result if the PBD is damaged or plugged by foreign material. In many cases a diagnosis can be made to determine whether a pressure change is caused by seal leakage or a change in PBD characteristics. Because the conditions of pressure, CBO flow, and vapor seal leakage are interrelated, these values must be known and evaluated simultaneously to provide such a determination.

While the BJ N-9000 seals have been redesigned to use ethylene propylene elastomer material and tungsten carbide for the rotating faces, the SU seals in use at Ft. Calhoun continue to use titanium carbide for the rotating faces. It was not feasible to change to tungsten carbide for the current face geometry. Despite several beneficial properties of tungsten carbide, it could not be used in the SU seal. Analysis showed that the face behavior under various operating conditions would be unacceptable. The elastomer seal O-ring material was changed to ethylene propylene, but the U-cups are still made of nitrile rubber because it was found that the ethylene propylene was not suitable to be molded into the U-cup shape.

The BJ SU seals were the design originally supplied with the RCPs. Ft Calhoun has decided not to convert to another type of seals as they have found the SU seals to give adequate service. Palisades has decided to convert three of the pumps to N-9000 seals. The B pump will run with the SU seal until the next refueling cycle. The plan is to convert to a N-9000 seal at that time. As in other seal designs used for BJ RCPs, the RCS pressure is broken down equally across the three lower stages. The equi-staged pressure breakdown is accomplished by bleeding a bypass (staging) flow of cooled primary water through a flow resistance path parallel to each seal stage. The controlled bleedoff (CBO) flow is about 1.0 gpm during normal operation (with all seal stages functioning properly). The function of the vapor stage is to prevent the CBO (now at about 50 psig) from leaking out to the containment. Any leakage past the vapor stage seal is piped through gravity passages and piping to the drain system. Figure A.5-1 presents a cross-section of a 4-stage SU seal. Figure A.5-2 presents a more detailed cross-section of a single SU seal stage.

A.6 References

A-1. Marsi, J. A., "Development of a 9 Inch (228 mm) Nuclear Primary Coolant Seal," Presented at the ASME/STLE Tribology Conference, Baltimore, MD, October 16-19, 1988

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Subject: Transmittal of Final Report for CEOG Task 1136

Attachment: CE NPSD-1199-P, "Model for Failure of RCP Seals Given Loss of Seal Cooling", Revision 00, July, 2000:
CE NPSD-1199, "Model for Failure of RCP Seals Given Loss of Seal Cooling", Revision 00, July, 2000 (Non-Proprietary Version)

Paul:

Attached is a copy of CE NPSD-1199-P, "Model for Failure of RCP Seals Given Loss of Seal Cooling", Revision 00. This report is the final deliverable for CEOG task 1136. This proprietary topical report is to be submitted to the NRC for review and approval so I have also prepared a non-proprietary version, CE NPSD-1199, which is also attached. Would you please transmit these documents to the PSASC members. Would you also arrange for this Topical Report to be transmitted to the NRC under a cover letter from the CEOG.

If you have any questions or comments, please call me at extension 3926.