Westinghouse Non-Proprietary Class 3

WCAP-16175-NP
Revision 0
CE NPSD-1199-NP
Revision 1

January 2004

Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants

CEOG Task - 1136
CEOG Task - 1189
CEOG Task - 2003

Westinghouse

LEGAL NOTICE

This report was prepared as an account of work sponsored by Westinghouse Electric Company LLC. Neither Westinghouse Electric Company LLC, nor any person acting on their behalf:

A. Makes any warranty or representation, express or implied including the warranties of fitness for a particular purpose or merchantability, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

WCAP-16175-NP, Rev. 0
CE NPSD-1199-NP, Rev. 01

Model for Failure of RCP Seals Given Loss of Seal Cooling in CE NSSS Plants

January 2004

Prepared by:

David J. Finnicum
Reliability & Risk Assessment

Reviewed by:

Raymond E. Schneider
Reliability & Risk Assessment

Reviewed by:

Virgil A. Paggen
Regulatory Compliance & Plant Licensing

Approved for Release:

Paul J. Hijeck, Acting Manager
Reliability & Risk Assessment

COPYRIGHT NOTICE

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)

LIST OF TABLES (cont'd)

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
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, BJ/SU	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
DC	Direct Current
EAC	Emergency AC power
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generator
EOP	Emergency Operating Procedure
EP	Ethylene Propylene
EPDM	Ethylene Propylene Diene Monomer
EPRI	Electrical Power Research Institute
ESFAS	Engineered Safeguards Features Actuation Signal
ESW	Essential Service Water, also 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
HRA	Human Reliability Analysis
IE	Initiating Event
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
LOSI	Loss of Seal Injection
LOSP	Loss of Site Power
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
NOP	Normal Operating Pressure
NOT	Normal Operating Temperature
NRC	Nuclear Regulatory Commission
NPRDS	Nuclear Plant Reliability Data System
NPSD	Nuclear Power Systems Document (ABB CE)
NSSS	Nuclear Steam Supply System
NU	Northeast Utilities
NUCLARR	Nuclear Computerized Library for Assessing Reactor Reliability
NUMARC	Nuclear Utility Management and Resource Council
OPPD	Omaha Public Power District

ACRONYMS (Cont'd)

Acronym	Definition
PBD	Pressure Breakdown Device
PCV	Pressure Control Valve
PO	Pop-Open
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Analysis
psia	Pounds per square inch, absolute pressure
psid	Pounds per square inch, differential 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
SG	Steam Generator
SI	Safety Injection
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 establish a model 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 NSSS plants have never experienced a simultaneous failure of all RCP seal stages. There have been individual 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 NSSS plants.

Interest by the Combustion Engineering Owners Group (CEOG) 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," Reference 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 both 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 NSSS plants, the CEOG authorized a project to develop a RCP Seal Failure model for loss of seal cooling conditions. The results of this effort are the subject of this report. This model:

- Evaluates the impact of influencing factors such as controlled bleed-off status and RCP operating status on the seal failure probability,
- Develops and quantifies a seal failure model, and
- Defines the expected leakage rates for various combinations of seal stage failures.

The RCP seal failure model is quantified using a combination of operating experience data, the results from past RCP seal tests, analytic models and expert opinion. This approach is consistent with that outlined by Brookhaven National Laboratories (BNL) in the "Guidance Document for Modeling of RCP Seal Failures," Reference 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 (GI-23), *Reactor Coolant Pump Seal Failure,* Reference 3, for resolution of this issue. These actions were taken on the basis of operational 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, Reference 4, soliciting comments on the understandings, findings and potential recommendations regarding GI-23 along with a draft Regulatory Guide, DG-1008, Reference 5. In August 1994, the NRC staff issued SECY-94-225, Reference 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's 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 BJ N-9000 seal, it is the balance sleeve outside diameter under the Quad-ring. In the case of the Sulzer seal, it is the 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 diameter 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 is typically in the range of 1.0 - 3.0 gpm. An increase in CBO flow indicates 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 will be accompanied by a change in seal staging pressures. A decrease in 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 an RCP's CBO line to automatically stop CBO flow if this flow increases to between 10 - 15 gpm. All CE NSSS 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 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 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 four RCPs since the CBO lines are manifolded downstream of the excess flow check valves.

Loss of Seal Cooling (pumps <u>without</u> 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. Loss of cooling also involves the RCP motor where the thrust and guide bearings depend on the cooling water for their proper operation.

Loss of Seal Cooling (pumps <u>with</u> seal injection):

Stoppage of both seal injection and component cooling water flow to the RCP. The simultaneous loss of both cooling sources would usually involve the loss of offsite power. Loss of cooling also involves the pump bearing assembly and the RCP motor where the thrust and guide bearings 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 3-stage seal cartridge, or the loss of 3 stages in a 4-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 two seal stages in a 4-stage seal cartridge requires 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 degradation is not synonymous with, nor does it necessarily lead to seal failure.

Seal Failure:

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

Seal Face Convergence:

Early seal development tests led to studies of the relationship between the shape of the gap between the faces, leak rate and the hydraulic balance of flat-faced seals. Tests 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, and
- 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.

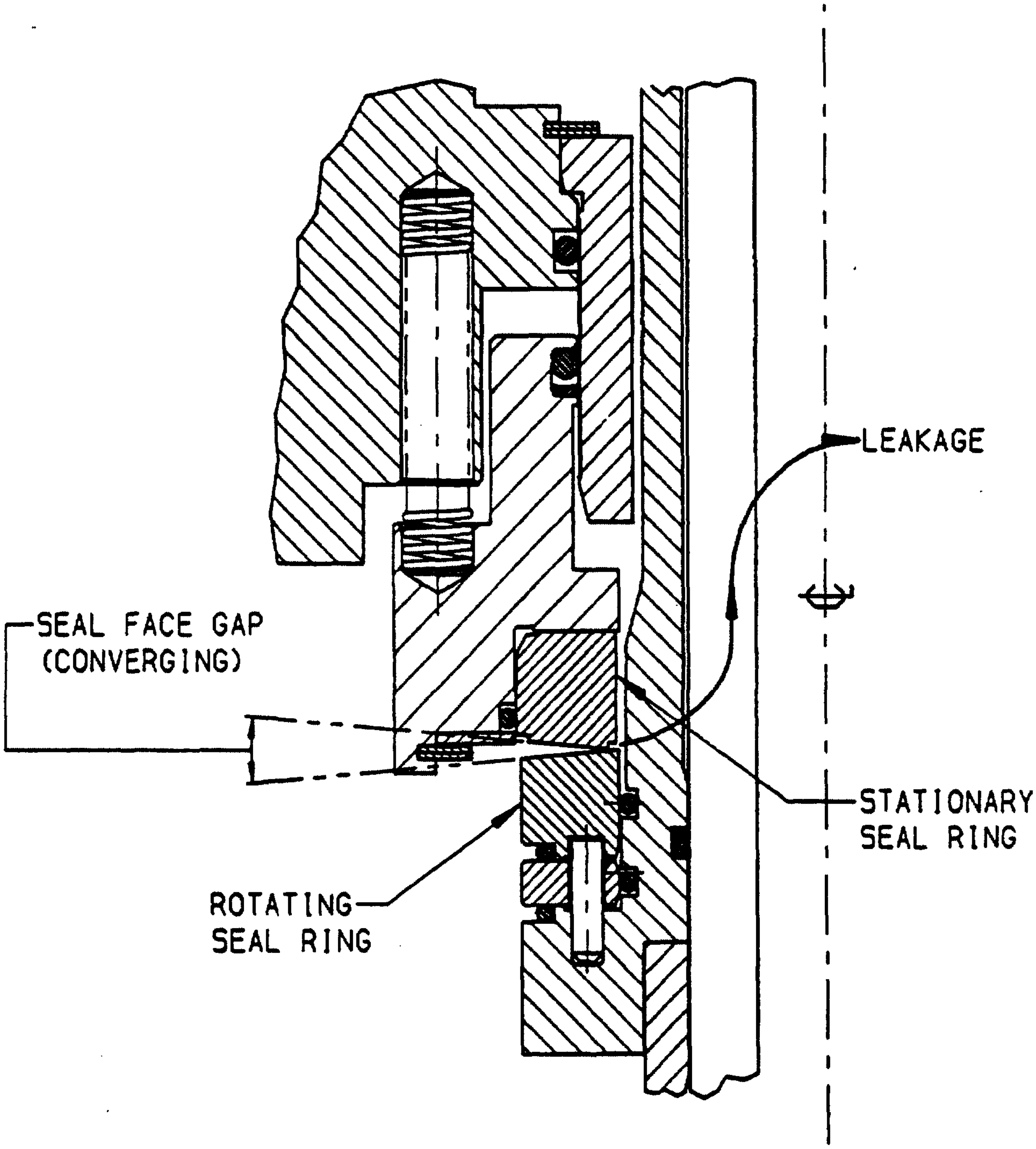
Seal Leakage:

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, 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.

Figure 2-1
Seal Face Operating Gap



This page intentionally blank.

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. Seal cartridge cooling is accomplished via the Component Cooling Water (CCW) system. CE System 80 plants (PVNGS Units 1, 2 and 3) employ CE-KSB pumps which originally used 3-stage seals made by KSB in Germany; they now use 3-stage seals designed by Sulzer. CE-KSB designs utilize seal cooling via seal injection and the CCW system, also termed the nuclear cooling system at PVNGS.

The original seal designs did not explicitly consider station blackout and loss of seal cooling conditions in the seal design stage. Pump manufacturers developed more robust seals as operating experience was gained, harsh operating environments were better understood, and analysis technology improved. These newer seals are specifically designed to cope with station blackout scenarios. The improved BJ seal is marketed as the N-9000 design; Sulzer (Bingham) also offered an improved three and 4-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 current 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.

Table 3.1-1
Comparison of Materials used in BJ/SU, N-9000 and Sulzer Designs

Component	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	Ethylene-Propylene
Seal type	Balanced Rotor	Stationary Balance	Balanced Stator®

Table 3.1-2
RCP Seal Types in Use at CE NSSS Plants

Seal Type[b, c]	Plant	Approximate Date of Installation
BJ N-7500 [d] (4-stage)	Fort Calhoun	6/2002
BJ N-9000 Seals (4-stage)	Arkansas 2	2 pumps 6-97, 2 pumps 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 three N-9000 seal stages 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.
d) N-7500 seals are equivalent to N-9000 with a slightly smaller diameter.

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 functional 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 CE-KSB RCPs, 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 NSSS 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 to pre-cool the primary water that 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 serve 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 4-stage RCP seal assembly is illustrated in Figure 3.2.1-1. The RCP seal assembly contains a seal cooling heat exchanger and a seal cartridge. The seal cooling heat exchanger cools the RCP seal leakage. The stage seal arrangement provides a means of establishing controlled lubrication of the RCP shaft with RCS internal coolant.

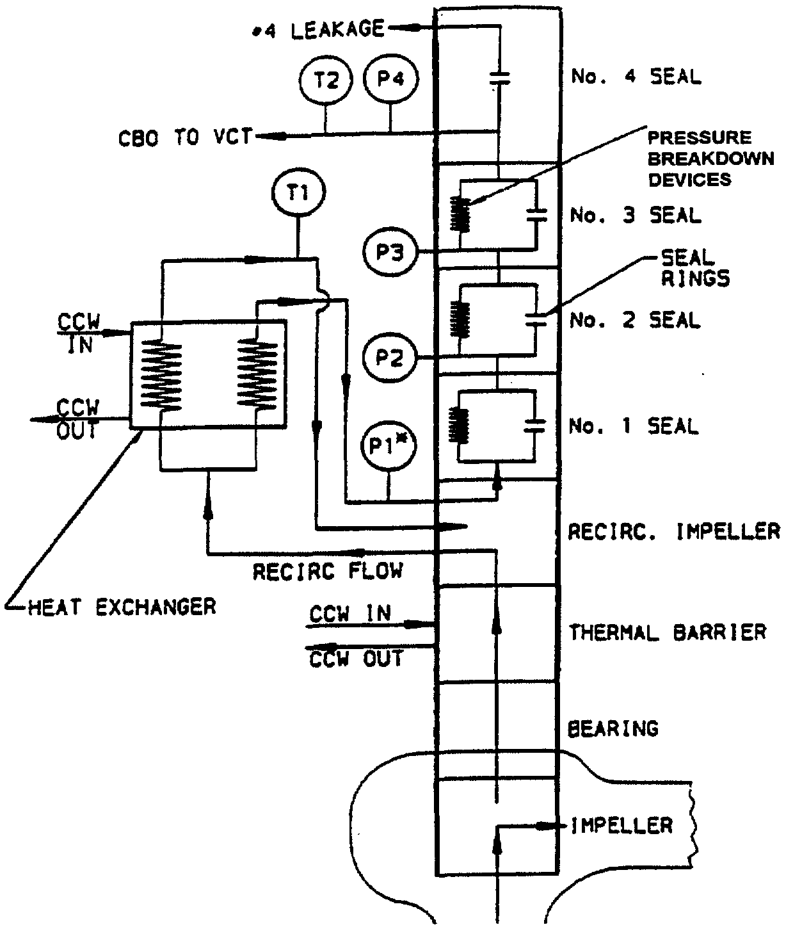
For proper functioning the seal cartridge passes a small amount of primary fluid as Controlled Bleedoff (CBO). During normal operation, CBO water (at about 550°F) enters the seal area through the annulus between the shaft and the cover at a rate of between 1.0 and 1.5 gpm (see for example Table 3.2-1). 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.

CE 4-stage 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 stage has one stationary seal face and one rotating seal 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 stage cavities. 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 seal faces for the first 3 stages. The PBDs consist of coiled tubes that offer resistance to fluid flow. These PBDs are equistaged such that each seal stage will take a proportionate part of the system pressure, with each of the first three seal stages taking approximately one third of the system pressure. The fourth (or vapor stage) operates at a low pressure (about 25-100 psig). Any leakage past the vapor stage 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 3 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.

Figure 3.2.1-1

Schematic of 4-stage RCP Seal Assembly



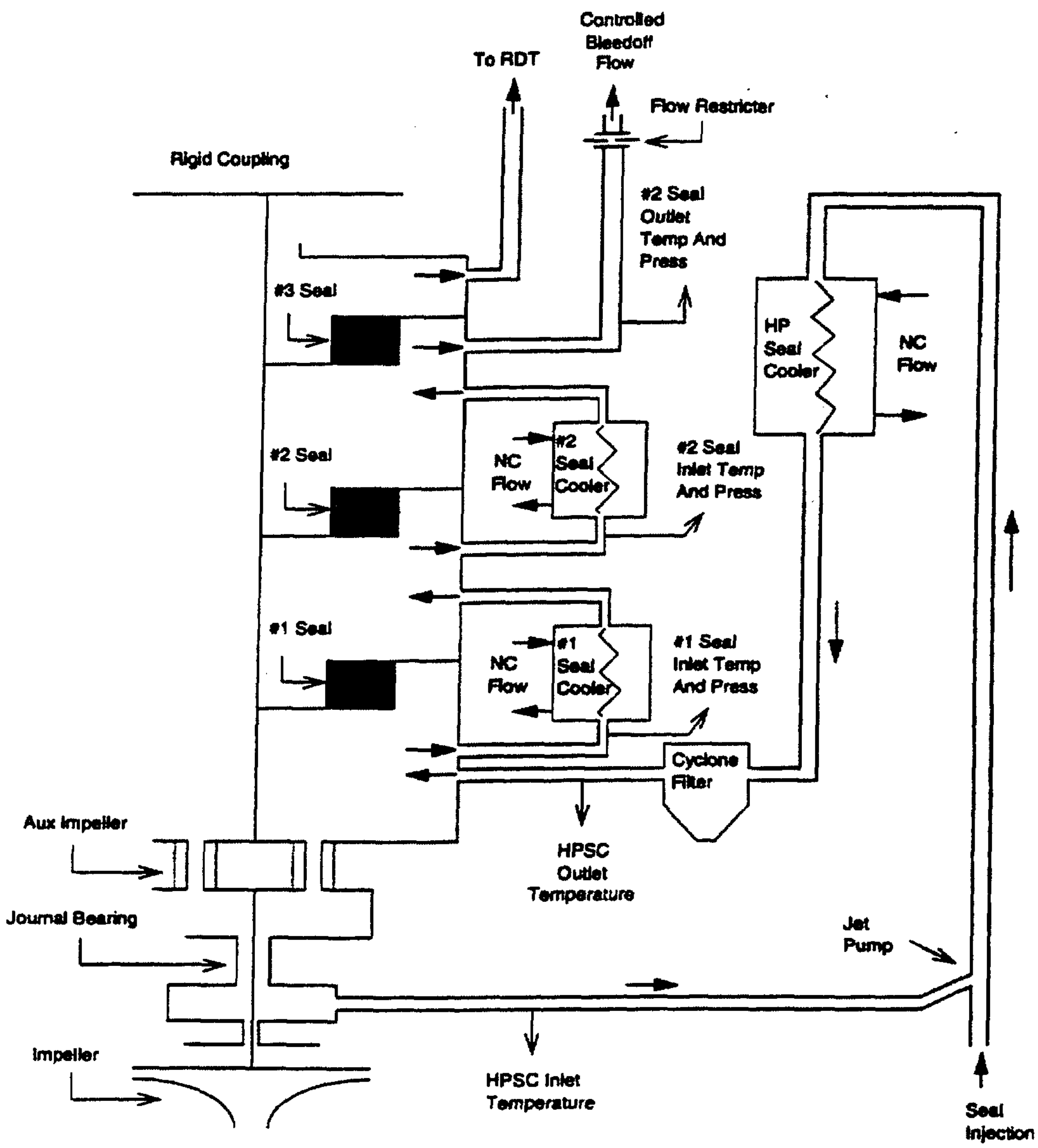
3.2.2 RCP Seal Operation: 3-stage Seal Design

Palo Verde Units 1, 2 and 3 were initially designed with CE-KSB reactor coolant pumps and are the only domestic CE PWRs that utilize a 3-stage seal design. While the seal dynamics are generally similar to that of the 4-stage unit, the 3-stage RCP seal has several unique features. First, the RCP seals for the Palo Verde units have two sources of seal cooling; a recirculation impeller circulates primary coolant into heat exchangers cooled by the CCW system and direct RCP seal injection. In the latter method, the charging pumps inject cool water from the Volume Control Tank directly into each 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 CE-KSB 3-stage seal is the design of the seal staging. These seals are designed such that the pressure drop across the 3 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 CE-KSB seals initially used in the PVNGS units have been replaced by a more robust Sulzer 3-stage design.

Figure 3.2.2-1
Simplified Schematic of 3-Stage RCP Seal



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.

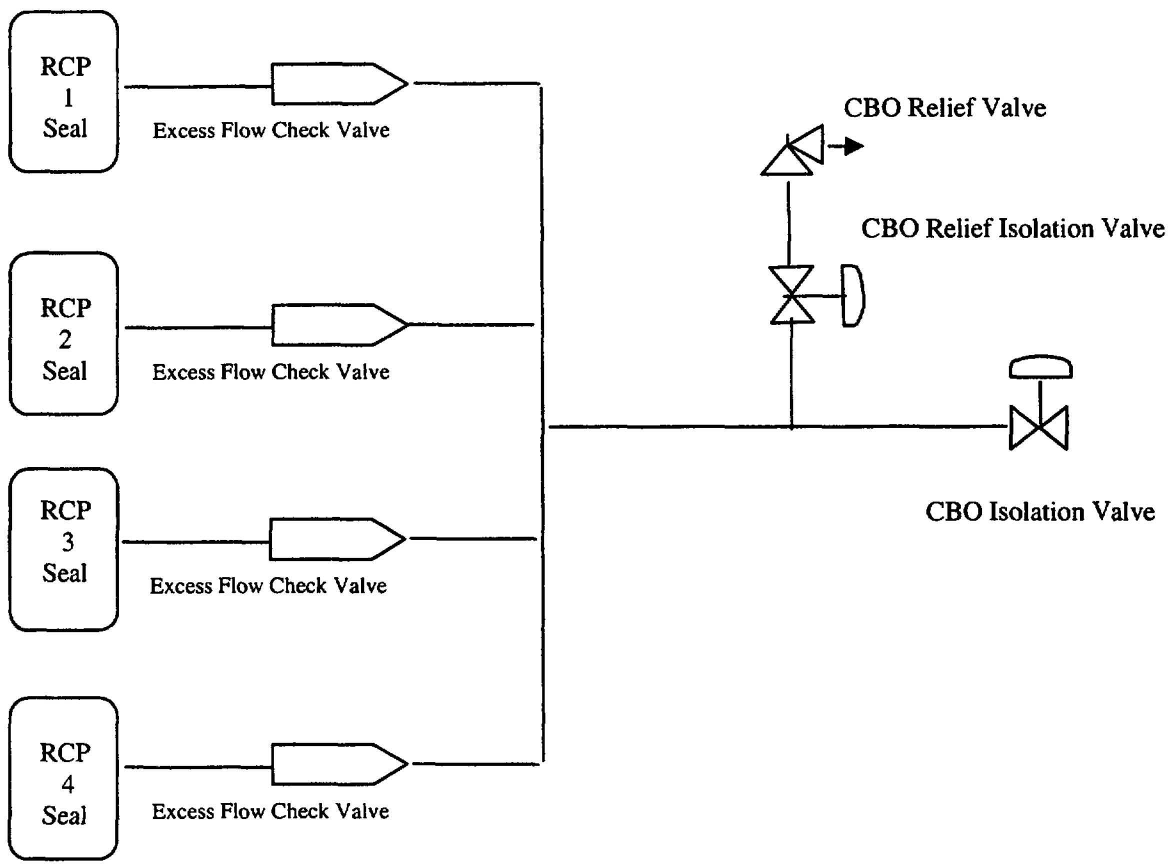
The CBO lines from the individual RCPs join in a common line, which contains the CBO isolation valve. This common line also includes a CBO relief valve, which will lift to relieve pressure in the CBO lines if the CBO isolation valve inadvertently closes. There is a CBO relief valve isolation valve between 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	22
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 3 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 ~ 250°F 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 use in 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, Reference 22. The results clearly show that [[

]][a,c] The Kalsi Engineering Tests, contracted by SCE (Reference 13) clearly indicate a high likelihood of high temperature [[ ]][a,c] elastomer survivability for periods in excess of eight hours. Post-test inspections indicated that, even after [[ ]][a,c] temperature exposure, the O-rings remained elastic, there was no guminess or embrittlement of the material and extrusion into the gap was slight [[ ]][a,c] 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

a,c

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 indicates 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 to CE-KSB RCPs.

- 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, Reference 2, identifies and models three seal stage failure mechanisms associated with Loss of Component Cooling Water (LOCCW) events. These are:

- Binding failure of the seal ring for the stage.
- Extrusion failure of secondary seal elastomers (O-ring Extrusion Failure) for the stage.
- Opening of stage 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 stage seals when exposed to low subcooling and two phase fluid conditions. Since the temperature and pressure may vary at each seal stage, the impact of these failure mechanisms can be different at each stage 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 could 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, Reference 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 elastometer varies between 0.01 and 0.04 inches, depending on pump and seal design.

BNL, Reference 2, considered binding failure of the seal to be a concern only for low temperature ("unqualified") elastomers. BJ 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 to the 3-stage CE-KSB RCP seal 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 face or the stationary seal face 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 are 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)

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					
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 stages 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 within the seal gap. Flashing in the gap will also change the pressure distribution within the seal face. Analytical models developed by AECL, Reference 22, 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 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 the 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.

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

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

Evidence of local seal stage "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 the seal stage to high temperature liquid aggravated the "pop-open" process by making it more difficult for the stage seal to reclose once the dynamic condition has been removed. To date the only evidence of seal stage "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 a station blackout event. 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 CE-KSB RCP seal 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 and post accident response of the plants 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 the bypass flow through the seal stage pressure breakdown device. A fourth vapor seal stage provides an additional pressure barrier. Each seal stage is normally operated at about 130°F to 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 3-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 stage is maintained by the controlled bleedoff flow from the RCS. For example, a CBO flow of 1 gpm in BJ RCP seals creates a pressure drop of approximately 700 psig across each of 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 stage seal faces. The vapor seal stage is operated at a pressure difference of 315 psig. The PBDs are designed such that the CBO flow is very small, less than 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, i.e., develop a new pressure breakdown. The loss of fluid resistance in the failed stage will result in an increased CBO flow. A complete stage failure will be sensed as a lack of ability of the seal stage to hold pressure.

Provided at least one hydrodynamic seal stage remains intact, the increased RCS leakage flow will be controlled to small levels by the non-bypassed pressure control devices internal to the RCP seal cartridge. 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)	[[ ]]^{a,c}	No PBDs bypassed. Minor leakage of CBO flow into Reactor Drain Tank.
Any one of first 3 stages (with or without vapor seal intact)	[[ ]]^{a,c}	Increased flow will be directed to CBO line if vapor seal stage intact.
Any two of first 3 stages (with or without vapor seal intact)	[[ ]]^{a,c}	Increased flow will be directed to CBO line if vapor seal stage intact.
Three lower PBD controlled seal stages failed catastrophically. Vapor seal stage intact	Plant specific – see Table 5.2-3	If all three lower PBDs fail catastrophically and the vapor stage is intact, the CBO flow would be limited by one of 3 factors. If CBO is fully isolated, the leakage flow would be limited by the leakage through the intact vapor stage seal, which would be small. If CBO is not isolated, then the CBO flow rate would be limited by the flow limiting check valves which, depending on the plant, will limit flow to between 10 and 15 gpm. If CBO flow is not isolated and the excess flow check valve fails, the values in Table 5.2-3 would bound the absolute maximum possible leakage rates because these values represent the maximum possible flow through the RCP thermal barriers and into the seals.
All seal stages failed catastrophically	Plant specific – see Table 5.2.3	With vapor seal stage 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 stage (or Stage III)	[[ ]]^{a,c}	Seal restaged such that the vapor stage pressure drops too ambient and each stage takes 50% of pressure drop.
Seal stage I or stage II failed	[[ ]]^{a,c}	Flow increase reflects loss of 43% of initial flow path resistance.
Two seal stages failed (I & III or II & III)	[[ ]]^{a,c}	Flow increase reflects loss of 57% of initial flow path resistance.
Two seal stages failed (I & II)	[[ ]]^{a,c}	Flow increase reflects loss of 86% of initial flow path resistance.
All seal stages failed catastrophically***	[[ ]]^{a,c}	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 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 is bounded by the RCP thermal barrier flow area which limits the total 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 RCP seal packages. The presence of narrower passages or additional resistance in the RCP seal packages 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 of all seals considered a limited seal gap opening of 0.01 inches. The resulting RCS leakage was estimated to [[ ]]^{a,c} 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**	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Calvert Cliffs 1& 2	BJ**	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
SONGS 2 & 3 and WSES (BJ design)	BJ**	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Palo Verde	KSB	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}

* Nominal hydraulic resistance (from CE NPSD-657-P, Ref 23).
** Leakage limited by the thermal barrier flow resistance. Actual flow would be less since additional flow resistance associated with the RCP seal package was not credited.

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 [[ ]]^{a,c} Failure of 4 stages will result in significant leakage into the containment. For the 3-stage RCP seal design, all stages must fail for RCS leakage to [[ ]]^{a,c} 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 between 10 and 15 gpm per pump. Cumulative leakage (multiple RCP leakages) 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 4-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 4-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 [[ ]]^{a,c} 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, 3-stage seal designs where two seal stages are non-functional will produce an enhanced RCS leakage of [[ ]]^{a,c} 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 [[ ]]^{a,c} for a period of

8 hours will result in a loss of [[ ]]^{a,c} 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. This section explores 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 4-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 3-stage RCP 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 3-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 plant 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 (and maximum seal temperature) will be about [[ ]]^{a,c}

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 stage cavities will be maintained [[ ]]^{a,c} (cf., Reference 17). At these temperatures no serious threat exists for seal failure. Delayed isolation of CBO flow will allow the lower seal stage 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 [[ ]]^{a,c} 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 stage (°F)**
BJ RCPs 4-Stage Seals	[[ ]]^{a,c}	[[ ]]^{a,c}
CE-KSB Pumps	[[ ]]^{a,c}	[[ ]]^{a,c}

During the station blackout test performed on the BJ N-9000 seal cartridge, Reference 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 4-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, Reference 17, indicate that even when CBO is isolated 1.5 hours into the event the local ambient temperature in the lower seals will [[ ]]^{a,c} A greater temperature drop is expected in the vapor stage. The relief valve setpoint was assumed to be 1200 psia (representative of Palo Verde Units) for the 3-stage seal design; 4-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	[[ ]]^{a,c}	1000	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Seal Cavity 2	1000	[[ ]]^{a,c}	1000	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Seal Cavity 3	1000	[[ ]]^{a,c}	1000	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Vapor Seal	1000	[[ ]]^{a,c}	1000	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}

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	[[ ]]^{a,c}	1200	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Seal Cavity 2	1200	[[ ]]^{a,c}	1200	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Vapor Seal	1200	[[ ]]^{a,c}	1200	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c*}

* 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. The cold leg temperature will be lower so the subcooled margin at the RCP will be greater than the subcooled margin based on the hot leg temperature.

5.3.2 Seal Conditions during a Loss of Component Cooling Water Event

Coolant for the RCP seal heat exchanger is typically 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 straightforward. CE NSSS 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:

- Actions for and timing of CBO isolation.
- 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 the 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 two to five minutes. Once tripped, the pumps will coast down and come to a stop in three to four 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 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. However, 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 [[ ]]^{a,c}. 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 BJ 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 BJ 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 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, °F	>50 (Note 2) very likely	> 25 required	20-50	>80	>50	>50	>50	20-30 (Note 5)	30 –60 (Note 11)
Subcooling on SBO, °F	30-50	> 25 required	20-50	20-50	24 - 50	30-50	<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, psi	1100	1000	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 flow path to the VCT, however, the isolation valve upstream of the CBO relief valve is not closed. So, CBO flow will continue through this flow path.
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	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 2	1800	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 3	1800	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Vapor Seal	1800	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c

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	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 2	1500	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 3	1500	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Vapor Seal	1500	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c

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	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 2	1200	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 3	1200	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Vapor Seal	1200	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c

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	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 2	1800	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Vapor Seal	1800	[[ ]]a,c	1800	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c

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	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 2	1500	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Vapor Seal	1500	[[ ]]a,c	1500	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c

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	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Seal Cavity 2	1200	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c
Vapor Seal	1200	[[ ]]a,c	1200	[[ ]]a,c	[[ ]]a,c	[[ ]]a,c

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 stage seal faces and minimizes the pressure drops across the internal stage seals. Both factors contribute to enhanced hydraulic stability of the seals and minimize the potential for seal failure due to the seal stage "pop-open" phenomena. The vapor stage 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 4-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	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Seal Cavity 2	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Seal Cavity 3	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}
Vapor Seal	[[ ]]^{a,c}	[[ ]]^{a,c}	[[ ]]^{a,c}

A failure of either stage 2 or stage 3 will result in a lower pressure at the entrance to the middle seal stage. When stage 2 is the intact seal stage, the entrance subcooling will decrease. In the LOCCW example, the entrance conditions will become saturated. When stage 2 fails in advance of stage 3, the stage 3 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 stage) will result in a seal pressure redistribution which, for hot standby conditions, will decrease the seal stage cavity pressure from [[ ]]^{a,c} Failure of the middle seal results in a projected increase in the vapor stage seal pressure from [[ ]]^{a,c} 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. Operating experience has shown that once a downstream seal stage has failed, failure of the upstream seal stage is increased (for all seal stages 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 that 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 test, 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 shaft motion depends upon RCP seal designs. Typical potential seal gaps vary from 0.02 to 0.07 inches. For the Sulzer pump seal design installed at Palo Verde, 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 cannot 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, four BJ/SU seals were uncooled for a period of 45 minutes while the RCPs continued operating; no increase in 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, Reference 10. No increased leakage or seal stage degradation was noted.

Seal manufacturers recommend that RCPs should not be restarted without station management approval if seal cooling has been lost for more than 30 minutes. 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 all RCP seals.

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 has been tested for the System 80 RCP motors and they were able to survive a thirty minute interval with no cooling. RCP motor performance tests were also included in the SONGS BJ/SU seal experimental test program, Reference 27. These tests confirmed acceptable motor performance for a period of more than 20 minutes after LOCW. Fort Calhoun operated their RCPs for a period of 45 minutes without CCW and did not experience a motor failure. Given this information, utilities should not credit failure of the RCP motor as a means of stopping the RCP given loss of CCW unless they have definitive documentation that this failure will occur within the time frame of interest for their RCPs.

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. This oil is cooled in heat exchangers, which depend on cooling water to function. If the supply of cooling water is lost, the oil temperature rises and the bearing surface temperature also rises. Oil quality (and therefore its lubricating properties) degrades at high temperature. The bearings are normally faced with a Babbitt, a lead alloy material with a fairly low melting point. RCP motor bearing temperature is monitored by sensors imbedded in the bearings.

This page intentionally blank.

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 three basic models; an environmental conditions event tree (Figure 6.1-1) and two RCP seal fault trees. The environmental conditions event tree is common to all CE seal designs. Two RCP seal 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 fault tree. The model as presented is for failure of a single RCP seal (all stages) given loss of seal cooling to that seal. It is the responsibility of the utility implementing this model to ensure that it is correctly applied for all RCP seals impacted by a given initiator.

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

6.1 Environmental Conditions Event Tree

The environmental condition tree is used to establish RCP seal stage conditions for use in estimating seal stage failure conditions. The tree has been constructed to represent the impact of LOSC on local seal conditions associated with events such as a station blackout event and a loss of component cooling water. The RCP Seal Failure event tree presented in this section has an initiator input and includes four top events. The conditions tree unfolds into twenty-one RCP Seal Failure conditions (RCPF-1 through RCPF-21). The following paragraphs provide a description of the components of the conditions tree.

a,c

a,c

a, c

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 a fault tree model to assess the potential for and magnitude of an RCP 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)

The 4-stage seal is common to CE plant designs prior to System 80. Failure of one or more RCP seal stages results in increased leakage from the RCS. However, analyses indicate that all seal stages have to fail prior to the onset of significant leakage from the RCS. Figure 6.2-1 presents the 4-stage seal fault tree model for failure of the seal given that CBO is isolated. Figure 6.2-2 presents the 4-stage seal fault tree model for failure of the seal given that CBO is not isolated.

a,c

6.2.2 3-Stage Seal Model (STAGE3)

a,c

a, c

[ ]

6.3 Additional Considerations

6.3.1 Comments on Failures of Multiple RCPs

The seal failure models developed in the previous sections are constructed for estimating failure of a single RCP seal cartridge. The total leak rate from all pumps with failed seals must be determined to establish core uncovery. Section 5.2 presents predicted seal cartridge leak rates for a various number of failed stages. Significant RCS leakage flows are not encountered until all RCP seal stages have failed (See Tables 5.2-1 through 5.2-3). The downstream excess flow check valve will limit the maximum CBO flow to less than 15 gpm for CE PWRs. Closure of the excess flow check valve will prevent flow from leaving the seal cartridge via the CBO line.

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

When multiple RCP seals are exposed to the same environmental conditions, the probability of multiple RCP seal cartridge failures should include a common cause factor to address the potential impact of common conditions. There is insufficient data available to calculate specific common cause factors such as β, γ, and δ. Therefore, engineering judgment is used in conjunction with the available operating experience data to estimate a common cause factor, Γ, which represents the probability that all affected RCP seals fail given that one of the affected RCP seals fails.

Table 8-1 presents the operating events involving loss of seal cooling to one or more RCPs. As shown on this table, there have been only seven events involving loss of cooling to multiple RCPs. Five of these events involved loss of cooling to all four RCPs (FCS-1, FCS-3, PV3-1, SL1-2, and SL2-3), one event involved loss of cooling to three RCPs (WSES3-1) and one event involving loss of cooling to two RCPs (SL2-2). For one of the events (SL2-3) in which cooling was initially lost to all four RCPs, cooling was restored for two of the four RCPs after about 14 minutes. The time frames for which RCP seal cooling was lost in these events ranged from 0.23 hours up to 4.5 hours. None of the events resulted in a seal failure and only two of these events involved stage failures on multiple pumps. In both events involving stage failures on multiple RCPs, the information on the stage failures is limited but they were most likely pop-open failures for stage 3 of 4-stage seals.

This data is insufficient to calculate the common cause failure factors for multiple RCP seal failures given the failure of one RCP seal, but it does provide solid evidence that failure of all seals exposed to loss of seal cooling is not guaranteed given that one fails. However, as stated above, there is a potential for common cause failure of all seals exposed to a loss of seal cooling. Because of the time dependent thermal aspects of the seal failure mechanisms, the potential for common cause failure of the seals is judged to be relatively low early in the event but will increase as the exposure time increases. Using engineering judgment in conjunction with the operating experience data in Table 8-1, the following Γ factors are used to estimate the potential for common cause failure of all RCP seals affected by a loss of cooling event given that one seal fails:

[ ]a,c

These parameters were estimated based on the following considerations:

1. Common cause failure is possible but not assured.
2. The likelihood of common cause failure increases with the exposure time.
3. A Γ of [[ ]]a,c is a reasonable estimate for the 0 to 1 hour time frame because all events involving loss of seal cooling to multiple RCPs in Table 8-1 had exposure times greater than 0.1 hours and none resulted in a common cause failure of the affected seals.

6.3.2 Core Damage and Core Uncovery

( )a,c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 1 of 7)

a.c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 2 of 7)

a.c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 3 of 7)

a.c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 4 of 7)

a.c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 5 of 7)

a,c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 6 of 7)

a,c

Figure 6.2-1: Model for Failure of 4-Stage RCP Seal Given CBO Isolated (Sheet 7 of 7)

a, c

Figure 6.2-2: Model for Failure of 4-Stage RCP Seal Given CBO Not Isolated (Sheet 1 of 5)

a,c

Figure 6.2-2: Model for Failure of 4-Stage RCP Seal Given CBO Not Isolated (Sheet 2 of 5)

a.c

Figure 6.2-2: Model for Failure of 4-Stage RCP Seal Given CBO Not Isolated (Sheet 3 of 5)

a,c

Figure 6.2-2: Model for Failure of 4-Stage RCP Seal Given CBO Not Isolated (Sheet 4 of 5)

a,c

Figure 6.2-2: Model for Failure of 4-Stage RCP Seal Given CBO Not Isolated (Sheet 5 of 5)

a,c

Figure 6.2-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 1 of 5)

a,c

Figure 6.2-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 2 of 5)

a,c

Figure 6.2-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 3 of 5)

a,c

Figure 6.2-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 4 of 5)

a.c

Figure 6.2-3: Model for Failure of 3-Stage RCP Seal Given CBO Isolated (Sheet 5 of 5)

a,c

Figure 6.2-4: Model for Failure of 3-Stage RCP Seal Given CBO Not Isolated (Sheet 1 of 3)

a,c

Figure 6.2-4: Model for Failure of 3-Stage RCP Seal Given CBO Not Isolated (Sheet 2 of 3)

a.c

Figure 6.2-4: Model for Failure of 3-Stage RCP Seal Given CBO Not Isolated (Sheet 3 of 3)

a,c

This page intentionally blank.

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 organized into the following three categories:

1. Loss of Seal Cooling with Operating RCP

   RCP seal performance tests investigating the RCP seal leakage during heatup following a limited duration simulated LOSC with operating RCPs. Tests are conducted at nominal RCS operating conditions. Typically, these events monitor 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 is 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 can withstand a locally harsh environment for extended periods.

7.1 Tests of Loss of Seal Cooling with Operating RCP

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 (Reference 16)

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 neither cause a rapid deterioration of the pump shaft rotary seals, static elastomer seals, stationary and rotating metal seal cartridge components nor 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 the San Onofre Nuclear Generating Station. Once the pump was at normal operating pressure and temperature, 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 this test. During the LOCCW the CBO was limited to 1.85 gpm and a seal bypass flow of 0.26 gpm was noted. Post-test 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 the 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 showed any noticeable indication of incipient U-cup extrusion.

As CBO was operational, the seal temperatures in all stages increased rapidly. The lower 3 stages indicated similar heatup with temperatures of all 3 stages exceeding 500°F. The vapor stage peak temperature reached about 400°F during the 30 minute LOCCW test. Vapor stage temperatures were lower as this last stage is subject to greater ambient heat loss and lower pressures.

It was noted that the maximum seal bleedoff increased from 0.92 gpm to 1.8 gpm at 24 minutes into the test. 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 a loss of seal cooling. In this test, SCE installed the approximately half-scale seal assembly on an operating pump at Alamitos Generating Station, Unit 3. The test results showed stable behavior during station blackout conditions. The seal did not exhibit unstable behavior any time during the test and there was no discernable increase in leakage. (See Reference 10.)

In December 1978, Byron Jackson performed a loss of seal cooling test using a SONGS reactor coolant pump with a BJ/SU seal cartridge (Reference 16). This test provided considerable data on seal performance during a loss of cooling event. 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 November 1, 1985 (Reference 10) were comparable to those from the earlier 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 slow 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 9 ½" 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 stage 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 good condition and could have continued to operate without cooling for an extended time, Reference 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 BJ 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.

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 stage seal, 1795 psig - middle stage seal, 1050 psig - upper stage seal and 590 psig - vapor stage seal. The high vapor stage 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. No seal stage completely failed during this test.

The pressure readings in each seal stage cavity indicate that all seal stages were retaining flow normally during most of the test. The upper seal stage 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 stage 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 stage 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 face gaps.

Based on the results of this test it was noted that sustained seal water temperatures greater than 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; all pressure containing housings and the seal sleeves were still within the drawing tolerances. The seal damage included a broken vapor stage 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.

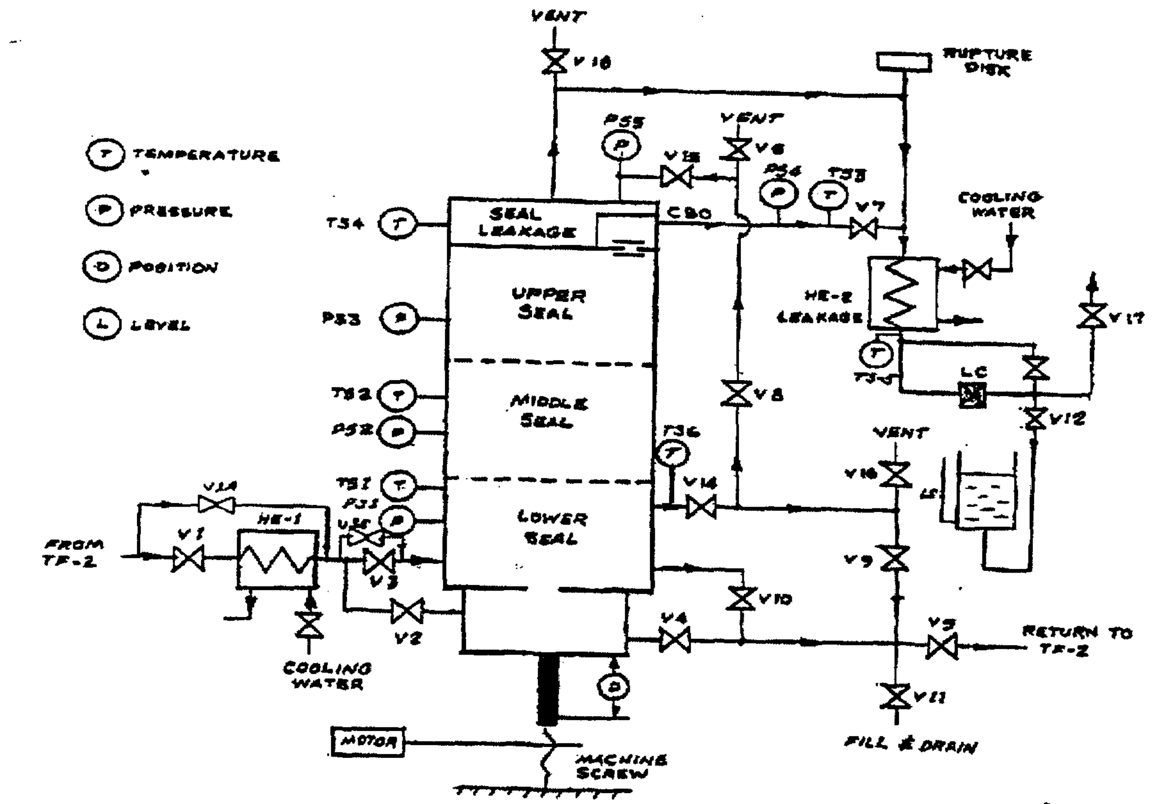
O-ring extrusion of the back-up ring seat gasket was evident in both the lower and upper mechanical seals during post test inspection. This O-ring extrusion was most likely due to the high temperature effects under pressure on the O-rings and, together with the Nitril U-cup degradation, may account for the occasional leaking of both of these seal stages 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 36-1/2 hours into 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 BJ N-9000 pump seal cartridge. The test provided information on the dynamic performance of a BJ 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 BJ N-9000 seal investigated had 3 stages. The fourth stage (or vapor stage) is optional, however it is used in all CE PWRs. The BJ 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 stage pressures simulated the response of the plant to a station blackout event. The initial shaft position was set at 0.114 inches.

Figure 7.2-1 Test Schematic for BJ N-9000 SBO Test



Including a pre-heat period, CBO was maintained at the nominal flow rate 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 a BJ 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 seal. The lower and middle seal stage temperatures reached and maintained temperatures in excess of 500°F during the initial phase of testing. The first stage seal experienced the greater temperature. The third 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.

CBO flow was isolated about 1.5 hours into the test (this was also identified as 0.5 hours after the lower seal reached the desired initial condition). 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 axial 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 stage 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 BJ 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 given the component exposures and the seal material thermal transient. This study identified that the weakest link in the seal was a stationary O-ring in the last stage. Failure of this O-ring exposed a small flow hole in the seal face to a pressure difference which created a pathway that bypasses the seal stage face. 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 seal faces.

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

During this test the seal stages 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 period without any measurable leakage. The seals stages did not exhibit signs of gumminess or embrittlement. Extrusion into gap clearances was minimal. A small decrease in seal face hardness (between 2 and 16 %) was noted.

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

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

Test Results for 650°F Elastomer Exposure

During this test the seals in the facility were exposed to 650°F environment until seal failure occurred. 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). Post-disassembly inspection indicated severe material breakdown. Elasticity of the seals was completely lost and stretching the seal caused permanent distortion.

This page intentionally blank.

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 past 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 events to be readily referenced in Section 9; identifier is 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.
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 ?	Stages Failed	Event Description
Fort Calhoun	4/17/74	FCS-1	BJ/SU	LOCCW	0.75	No	0	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	1	Loss of CCW to all four RCPs resulted in one failed stage on one pump. Seals changed on all four pumps after incident.
Fort Calhoun	4/28/81	FCS-3	BJ/SU	LOCCW	1	No	0	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.
Millstone 2	11/15/84	MNS2-1	BJ/SU	LOCCW	9	No	0	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 ?	Stages Failed	Event Description
Millstone 2	11/16/84	MNS2-2	BJ/SU	LOCCW	5 hrs	No	1	On November 16, while in 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 with all lower stages intact. Pressure would be of the order of 1400 psig with the lower stage completely failed), indicating middle stage degradation. The probable cause of the P-40B lower seal failure is a result of the temperatures to which the seals were exposed indicating possible O-ring and U-cup damage (cooking) and possible seal ring heat checking. Lower stage failure was caused by overheating of the lower elastomer material (likely to be nitrile). High pressure and large subcooling margin suggests lowest stage not subject to "pop-open" phenomena. Since CBO was not isolated, third stage was exposed to a pop-open condition. However, "pop-open" was not noted.
Palo Verde 2	4/4/86	PV2-1	KSB	LOCCW LOSI	3	Yes (after 18 min.)	0	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. The affected RCP was placed back into operation. When operating at hot standby, automatic actuation to all 4 channels of RPS occurred 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. Approximately 3 months later, While operating in mode 1 (power operation) at 30% reactor power, leakage was identified in the RCS from the RCP 2B seals. Plant was shutdown/cooled down to replace all 4 RCP seals. Failure was attributed to degradation incurred following the April 1986 incident on RCP 2B. The cause was determined to be the strainer flushing techniques employed at the time.

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 ?	Stages Failed	Event Description
Palo Verde 3	3/3/89	PV3-1	KSB	LOCCW/ LOSI	1.5	No	0	LOSP resulted in a simultaneous loss of seal injection and CCW 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. Thermal transient caused by the flow of hot RCS water. Near normal Controlled Bleedoff flowrates with no interstage cooling or Seal Injection damaged all 3 seal stages by thermally distorting the sealing surfaces of the stationary (carrier) and rotating (carbon) rings beyond their maximum allowable circumferential waviness (except second stage) and radial flatness rendering their hydrodynamic sealing capability questionable. (RCP1B not operated after seal press/breakdown noted) and their hydrostatic sealing capability poor. (1.25 gpm leakage.) The third stage was most severely damaged with the inner steel ring and carbon ring protruding from the assembly. Temperatures necessary to cause this are 149°F (Steel) and 205°F (Carbon). These disassembly temperatures are estimated to have been achieved in the third stage rotating element in less than one minute after initiation of the flow (approx 2.5 gpm) and temperatures (approx 400°F) of RCS water observed. One of four pumps exhibited failure of seal stage #3. Also, the actual failure and leakage of the Unit-3 CE-KSB seals in 1989 was because the rotating seal face disassembled due to the thermal expansion. The KSB carbon seal was shrunk-fit into a steel ring. At 150-205°F, the carbon became loose. This phenomenon cannot happen on the current style of Sulzer seals. This failure represents a mechanism unique to the KSB seal face design. Therefore this was not counted and the event was used only for evaluation of elastomer performance.

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 ?	Stages Failed	Event Description
Palo Verde 1	11/21/83	PV1-T	KSB	Test	0.6	Yes	0	Loss of total seal cooling at NOP/NOT conditions. CBO isolated. Peak stage three temperature < 135°F. No significant temperature transient was noticed when CBO isolated.
St. Lucie 1	4/15/77	SL1-1	BJ/SU	LOCCW	0.23 – 0.5	No	0	Loss of containment instrument air resulted in loss of CCW to RCP Seals at St. Lucie Unit 1. All seals were replaced.
St. Lucie 1	6/11/80	SL1-2	BJ/SU	LOCCW	1.5	No	0	Operating at full power, loss of CCW lasted 1.5 hrs, but plant was placed on shutdown cooling for 8 hrs. No leakage or degradations were noted; all seals were replaced.
St. Lucie 2	8/26/80	SL2-T	BJ/SU	SBO	>50	No	0	Test 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 confirmed that the seals can withstand SBO for an extensive time.
St. Lucie 2	12/19/84	SL2-2	BJ/SU	LOCCW	0.5	No	2	Pumps 2B1 and 2B2 seals failed due to loss of CCW caused by loss of power to CCW valves. Indications are that the seals did not completely fail but 3rd stage on each of the affected RCPs probably failed (pop-open). 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	2	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	0	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	0	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 3gpm. 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 ?	Stages Failed	Event Description
Waterford 3	2/20/85	WSES3 -1B	B-J	LOCCW	0.67	No	0	The CCW Containment Isolation Valves (CIVs) closed, securing cooling water flow to the RCP seal coolers, upon receiving a containment spray actuation signal. 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 three 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 three 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. Three 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	1	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

a,c

[ ]^{a,c}

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

[ ]^{a,c}

a,c

a, c

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

Plant	Date	Event No	No. of RCPs affected	Duration of Loss (hrs)	Pump Operating Y or N?	CBO isolated? Y or N?	Nitrile U-cups? (BJ/SU pumps)	Used to quantify Elastomer failure?	# Stages Exposed to High Temperature	Elastomer Failure Y or N?	Used to quantify Pop-Open (b)	# Stages subject to Pop-Open	# Stages failed due to Pop-Open	Reference(s)	Comment

a,c

NOTES for Table 9.1-1

a,c

9.2 Quantification of Seal Failure Parameters

a,c

9.2.1 RCP Stage Failure due to Elastomer Degradation

a,c

a,c

a,c

Table 9.2-1
Elastomer Failure Probability Calculation

Event ID	Date	Duration	Number of Pumps	Stages Exposed to Thermal Transient during Interval (Vapor Stage Not Counted)				
				>0.1 Hr < D ≤ 1 Hr	1 Hr < D ≤ 2 Hr	2 Hr < D ≤ 4 Hr	4 Hr < D ≤ 8 Hr	8 Hr < D ≤ 24 Hr

a,c

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

- **CONDITION 1: CBO NOT ISOLATED**

a,c

Table 9.2-2 Elastomer Failure Probability Given CBO not Isolated					
BJ/SU Seals with Nitrile U-cups					
Basic Event	**Time Frame**				
	>0.1 Hr < D ≤ 1 Hr	**1 Hr < D ≤ 2 Hr**	**2 Hr < D ≤ 4 Hr**	**4 Hr < D≤ 8 Hr**	**8 Hr < D ≤ 24 Hr**

a,c

a,c

Table 9.2-3 Elastomer Failure Probability Given CBO not Isolated					
N-9000 and Sulzer Balanced Stator 4 Stage Seals with EP Elastomers					
Basic Event	**Time Frame**				
	>0.1 Hr < D ≤ 1 Hr	**1 Hr < D ≤ 2 Hr**	**2 Hr < D ≤ 4 Hr**	**4 Hr < D ≤ 8 Hr**	**8 Hr < D ≤ 24 Hr**

a,c

Table 9.2-4 Elastomer Failure Probability Given CBO not Isolated					
Sulzer Balanced Stator 3-Stage Seals with EP Elastomers					
Basic Event	**Time Frame**				
	>0.1 Hr <D ≤ 1 Hr	**1 Hr < D ≤ 2 Hr**	**2 Hr < D ≤ 4 Hr**	**4 Hr < D≤ 8 Hr**	**8 Hr < D ≤ 24 Hr**

a,c

- **CONDITION 2: CBO ISOLATED**

a,c

a,c

a,c

Table 9.2-5 Elastomer Failure Probability Given CBO Isolated Within 20 Minutes					
BJ/SU Seals with Nitrile U-cups					
Basic Event	Time Frame				
	>0.1 Hr < D ≤ 1 Hr	1 Hr < D ≤ 2 Hr	2 Hr < D ≤ 4 Hr	4 Hr < D ≤ 8 Hr	8 Hr < D ≤ 24 Hr

a,c

Table 9.2-6 Elastomer Failure Probability Given CBO Isolated Within 20 Minutes					
N-9000 and Sulzer Balanced Stator Seals					
Basic Event	Time Frame				
	>0.1 Hr < D ≤ 1 Hr	1 Hr < D ≤ 2 Hr	2 Hr < D ≤ 4 Hr	4 Hr < D ≤ 8 Hr	8 Hr < D ≤ 24 Hr

a,c

Table 9.2-7 Elastomer Failure Probability Given CBO Isolated Within 20 Minutes					
Sulzer Balanced Stator 3-Stage Seals with EP Elastomers					
Basic Event	Time Frame				
	>0.1 Hr < D ≤ 1 Hr	1 Hr < D ≤ 2 Hr	2 Hr < D ≤ 4 Hr	4 Hr < D ≤ 8 Hr	8 Hr < D ≤ 24 Hr

a,c

Table 9.2-8 Elastomer Failure Probability Given CBO Isolated Within 10 Minutes (SBO only)					
BJ/SU Seals with Nitrile U Cups					
Basic Event	**Time Frame**				
	>0.1 Hr < D ≤ 1 Hr	**1 Hr < D ≤ 2 Hr**	**2 Hr < D ≤ 4 Hr**	**4 Hr < D ≤ 8 Hr**	**8 Hr < D ≤ 24 Hr**

a,c

Table 9.2-9 Elastomer Failure Probability Given CBO Isolated Within 10 Minutes (SBO only)					
N-9000 and Sulzer Balanced Stator Seals					
Basic Event	**Time Frame**				
	>0.1 Hr < D ≤ 1 Hr	**1 Hr < D ≤ 2 Hr**	**2 Hr < D ≤ 4 Hr**	**4 Hr < D ≤ 8 Hr**	**8 Hr < D ≤ 24 Hr**

a,c

Table 9.2-10 Elastomer Failure Probability Given CBO Isolated Within 10 Minutes (SBO only)					
Sulzer Balanced Stator 3-Stage Seals with EP Elastomers					
Basic Event	**Time Frame**				
	>0.1 Hr < D ≤ 1 Hr	**1 Hr < D ≤ 2 Hr**	**2 Hr < D ≤ 4 Hr**	**4 Hr < D ≤ 8 Hr**	**8 Hr < D ≤ 24 Hr**

a,c

9.2.2 Random Failure Probability

a,c

Table 9.2-11 summarizes the RCP failure contribution to random RCP failure probabilities.

Table 9.2-11
Random RCP Seal Stage Failure Probability

Plant Type	T < 1 hr	0 hr < T < 2 hrs	0 hrs < T < 4 hrs	0 < T < 8 hrs	0 < T < 24 hrs

a,c

9.2.3 Hydraulic Instability/Pop-Open and Stage Failure

a,c

a,c

Table 9.2-12
RCP Seal Pop-Open Failure Probability Calculation

			Stages Exposed To Thermal Transient (Vapor Stage Not Counted)				
Event ID	**Date**	**Duration**	**Number of Pumps**	**Stages Initially Subject to < 50°F Subcooling**	**Associated Stage Failures**	**Stages Subsequently Subject to < 50°F Subcooling**	**Associated Stage Failures**

a,c

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

- **Condition 1: CBO Isolated and RCS Cold Leg Subcooled**

a,c

Table 9.2-13A Stage Pop-Open Failure Probability When RCS is Subcooled and CBO is Isolated		
BJ/SU Seals		
Basic Event	Probability of Failure	Reference

a,c

a,c

Table 9.2-13B Stage Pop-Open Failure Probability When RCS is Subcooled and CBO is Isolated		
N-9000 and Sulzer Balanced Stator Seals		
Basic Event	Probability of Failure	Reference

a,c

a,c

Table 9.2-13C presents the resultant stage failure probabilities for the 3-stage Sulzer Balanced Stator seals given CBO isolated and RCS subcooled.

Table 9.2-13C Stage Pop-Open Failure Probability When RCS is Subcooled and CBO is Isolated		
3-Stage Sulzer Balanced Stator Seals		
Basic Event	Probability of Failure	Reference

a,c

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

a,c

Table 9.2-14A Stage Pop-Open Failure Probability When RCS Subcooling < 50°F and CBO is Isolated		
BJ/SU Seals		
Basic Event	Probability of Failure	Reference

a,c

a,c

a,c

Table 9.2-14B Stage Pop-Open Failure Probability When RCS Subcooling < 50°F and CBO is Isolated		
N-9000 and Sulzer Balanced Stator Seals		
Basic Event	Probability of Failure	Reference

a,c

The discussion above for Table 9.2-14B is also applicable to the Sulzer Balanced Stator 3-stage seal design except that there is one less stage. Table 9.2-14C presents the resultant stage failure probabilities for the Sulzer Balanced Stator 3-stage seals given CBO isolated and RCS saturated.

Table 9.2-14C Stage Pop-Open Failure Probability When RCS Subcooling < 50°F and CBO is Isolated		
Sulzer Balanced Stator 3-stage Seals		
Basic Event	Probability of Failure	Reference

a,c

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

a,c

Table 9.2-15A presents the pop-open probabilities by stage for the BJ/SU 4-stage seals.

a,c

Table 9.2-15A Stage Pop-Open Failure Probability When RCS is Subcooled and CBO is Not Isolated		
BJ/SU Seals		
Basic Event	Probability of Failure	Reference

a,c

Table 9.2-15B Stage Pop-Open Failure Probability When RCS is Subcooled and CBO is Not Isolated		
N-9000 and Sulzer Balanced Stator 4 Stage Seals		
Basic Event	Probability of Failure	Reference

a,c

The discussion above for Table 9.2-15B is also applicable to the Sulzer Balanced Stator 3-stage seal design except that there is one less stage. Table 9.2-15C presents the resultant stage failure probabilities for the Sulzer Balanced Stator 3-stage seals given CBO not isolated and RCS subcooled.

Table 9.2-15C Stage Pop-Open Failure Probability When RCS is Subcooled and CBO is Not Isolated		
Sulzer Balanced Stator 3-Stage Seals		
Basic Event	Probability of Failure	Reference

a,c

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

a,c

Table 9.2-16A **Stage Pop-Open Failure Probability When RCS Subcooling < 50°F and CBO is Not Isolated**		
BJ/SU Seals		
Basic Event	Probability of Failure	Reference

a,c

a,c

Table 9.2-16B **Stage Pop-Open Failure Probability When RCS Subcooling < 50°F and CBO is Not Isolated**		
N-9000 and Sulzer Balanced Stator 4 Stage Seals		
Basic Event	Probability of Failure	Reference

a,c

The discussion above for Table 9.2-16B is also applicable to the Sulzer Balanced Stator 3-stage seal design except that there is one less stage. Table 9.2-16C presents the resultant stage failure probabilities for the Sulzer Balanced Stator 3-stage seals given CBO not isolated and RCS subcooling < 50°F.

Table 9.2-16C **Stage Pop-Open Failure Probability When RCS Subcooling < 50°F and CBO is Not Isolated**		
Sulzer Balanced Stator 3-Stage Seals		
Basic Event	Probability of Failure	Reference

a,c

9.2.4 Common Cause Relationships

a,c

9.2.5 Pre-Existing Failure

a,c

9.2.6 Excess Flow Check Valve Fails to Limit Flow

a,c

a,c

9.2.7 Vapor Stage Leaks Enough to Restage Seal

a,c

9.3 Quantification of the Event Tree and Fault Tree Models

a,c

a,c

Table 9.3-1A
RCP Seal Failure Fault Tree Basic Event Probabilities for the BJ/SU Seal Design
CBO Isolated within 20 minutes and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-1B
RCP Seal Failure Fault Tree Basic Event Probabilities for the BJ/SU Seal Design
CBO Isolated within 20 minutes and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-1C
RCP Seal Failure Fault Tree Basic Event Probabilities for the BJ/SU Seal Design
CBO Not Isolated and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-1D
RCP Seal Failure Fault Tree Basic Event Probabilities for the BJ/SU Seal Design
CBO Not Isolated and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-1E RCP Seal Failure Fault Tree Basic Event Probabilities for the BJ/SU Seal Design						
CBO Isolated within 10 minutes and RCS Cold Leg Subcooling > 50°F						
Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-1F RCP Seal Failure Fault Tree Basic Event Probabilities for the BJ/SU Seal Design						
CBO Isolated within 10 minutes and RCS Cold Leg Subcooling < 50°F						
Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-2A
RCP Seal Failure Fault Tree Basic Event Probabilities for the N-9000 and Sulzer Balanced Stator Seal Design
CBO Isolated within 20 minutes and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-2B
RCP Seal Failure Fault Tree Basic Event Probabilities for the N-9000 and Sulzer Balanced Stator Seal Design
CBO Isolated within 20 minutes and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-2C
RCP Seal Failure Fault Tree Basic Event Probabilities for the N-9000 and Sulzer Balanced Stator Seal Design
CBO Not Isolated and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

Table 9.3-2D
RCP Seal Failure Fault Tree Basic Event Probabilities for the N-9000 and Sulzer Balanced Stator Seal Design
CBO Not Isolated and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

Table 9.3-2E
RCP Seal Failure Fault Tree Basic Event Probabilities for the N-9000 and Sulzer Balanced Stator Seal Design

CBO Isolated within 10 minutes and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-2F
RCP Seal Failure Fault Tree Basic Event Probabilities for the N-9000 and Sulzer Balanced Stator Seal Design

CBO Isolated within 10 minutes and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-3A
RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage Sulzer Balanced Stator Seal Design

CBO Isolated within 20 minutes and RCS Cold Leg Subcooling > 50°F						
Basic Event	Time Frame (Hours)					Reference
	$0.1 < T \leq 1$	$0.1 < T \leq 2$	$0.1 < T \leq 4$	$0.1 < T \leq 8$	$0.1 < T \leq 24$	

a,c

Table 9.3-3B
RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage Sulzer Balanced Stator Seal Design

CBO Isolated within 20 minutes and RCS Cold Leg Subcooling < 50°F						
Basic Event	Time Frame (Hours)					Reference
	$0.1 < T \leq 1$	$0.1 < T \leq 2$	$0.1 < T \leq 4$	$0.1 < T \leq 8$	$0.1 < T \leq 24$	

a,c

Table 9.3-3C
RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage Sulzer Balanced Stator Seal Design
CBO Not Isolated and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-3D
RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage Sulzer Balanced Stator Seal Design
CBO Not Isolated and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	0.1< T ≤ 1	0.1< T ≤ 2	0.1< T ≤ 4	0.1< T ≤ 8	0.1< T ≤ 24	

a,c

Table 9.3-3E
RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage Sulzer Balanced Stator Seal Design

CBO Isolated Within 10 Minutes and RCS Cold Leg Subcooling > 50°F

Basic Event	Time Frame (Hours)					Reference
	$0.1 < T \leq 1$	$0.1 < T \leq 2$	$0.1 < T \leq 4$	$0.1 < T \leq 8$	$0.1 < T \leq 24$	

a,c

Table 9.3-3F
RCP Seal Failure Fault Tree Basic Event Probabilities for the 3-Stage Sulzer Balanced Stator Seal Design

CBO Isolated Within 10 Minutes and RCS Cold Leg Subcooling < 50°F

Basic Event	Time Frame (Hours)					Reference
	$0.1 < T \leq 1$	$0.1 < T \leq 2$	$0.1 < T \leq 4$	$0.1 < T \leq 8$	$0.1 < T \leq 24$	

a,c

Table 9.3-4
Summary of Conditional RCP Seal Failure Probabilities for Various CE PWR Seal Designs

RCS Conditions	BJ/SU 4-Stage Seals				
	Time Frame				
	0.1 to 1 Hr	0.1 to 2 Hr	0.1 to 4 Hr	0.1 to 8 Hr	0.1 to 24 Hr

a,c

Table 9.3-4 (Continued)
Summary of Conditional RCP Seal Failure Probabilities for Various CE PWR Seal Designs

RCS Conditions	N-9000 & Sulzer Balanced Stator 4-Stage Seals					Sulzer Balance Stator 3-Stage Seal				
	Time Frame					Time Frame				
	0.1 to 1 Hr	0.1 to 2 Hr	0.1 to 4 Hr	0.1 to 8 Hr	0.1 to 24 Hr	0.1 to 1 Hr	0.1 to 2 Hr	0.1 to 4 Hr	0.1 to 8 Hr	0.1 to 24 Hr

a,c

9.4 Sensitivity Studies

a,c

Table 9.4-1 presents the results of these sensitivity studies for two selected evaluation conditions: 1) CBO Isolated at 20 minutes with RCS Subcooling > 50°F and 2) CBO Not Isolated with RCS Subcooling < 50°F.

Table 9.4-1
Comparison of Conditional Failure Probabilities

Seal Type	Evaluation Conditions	Nominal Conditional Failure Probability	Case 1: Pop-Open Lower Limit	Case 2: Vapor Seal Pop-Open Guaranteed	Case 3: Low temp. exposure modeling

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 CE NSSS 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 3-stage.

10.1 <u>Sample Case 1: Station Blackout induced RCP Seal LOCA</u>

This section estimates the probability of a station blackout induced RCP seal LOCA. Given a LOOP event, RCP seal cooling is still available if the diesel generators start and run. This calculation assumes a LOOP event followed by failure of both EDGs to start (no AAC capability is assumed). Failure of the diesel generators to run is not included in this calculation as the probability is about an order of magnitude less than failure to start. In a full plant PRA, all combinations resulting in a SBO would be included. 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)

All RCPs are tripped during a SBO. The model was evaluated for the 0.1 to 4 hour time frame with CBO not Isolated and RCS subcooling > 50°F for the three types of RCP seals of interest.

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. This is not a core damage frequency. The core damage frequency contribution would be evaluated using the associated probability of failure for the mitigating systems. In establishing the probability of a loss of coolant event due to failure of the RCP seals, the conditional probability of RCP failure obtained from Section 9 is multiplied by four to reflect the exposure of 4 RCPs to a similar degrading environment. This example does not include common cause failure of multiple seals because the intent is only to calculate the probability of an RCP seal LOCA and not the size of the LOCA. The number of seals failed would impact the time to core uncovery and hence the time available to mitigate the event. This would be covered in a full plant PRA.

Table 10.1-1
Frequency of SBO induced Seal LOCA

Seal Type	Conditional Failure Probability (per pump)	Reference Table	Event Frequency (Per Year)

a, c

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 will 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 the RCP seal 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 and depending upon the procedures, the RCS subcooling may be less than 50°F. LOCCW is not recovered for 4 hours. Note that for plants with the Sulzer 3-stage Balance Stator seals, seal injection must also fail before all seal cooling is lost.

The following values are representative of this scenario:

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

The resulting probability of this event propagating into a small LOCA is calculated by multiplying the above probabilities by the conditional RCP seal probability. The LOCCW scenario was evaluated for three specific sets of RCS conditions; 1) RCS subcooling > 50°F and CBO not isolated, 2) RCS subcooling > 50°F and CBO isolated within 20 minutes and 3) RCS subcooling < 50°F and CBO not isolated. All cases were evaluated for the 0.1 to 4 hour time frame. Results are summarized in Tables 10.2-1, 10.2-2 and 10.2-3.

Table 10.2-1 Frequency of LOCCW Induced Seal LOCA Case 1			
Evaluation Conditions: CBO Not Isolated, RCS Subcooling > 50°F, 0.1 to 4 hours			
Seal Type	Conditional Failure Probability (per pump)	Reference Table	Event Frequency (per Year)

a, c

Table 10.2-2 Frequency of LOCCW Induced Seal LOCA Case 2			
Evaluation Conditions: CBO Isolated within 20 minutes, RCS Subcooling > 50°F, 0.1 to 4 hours			
Seal Type	Conditional Failure Probability (per pump)	Reference Table	Event Frequency (per Year)

a, c

Table 10.2-3 Frequency of LOCCW Induced Seal LOCA Case 3			
Evaluation Conditions: CBO Not Isolated, RCS Subcooling < 50°F, 0.1 to 4 hours			
Seal Type	Conditional Failure Probability (per pump)	Reference Table	Event Frequency (per Year)

a, c

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.

This page intentionally blank.

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, those less than 4 hours. 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.

This page intentionally blank.

12.0 REFERENCES

1. CE-NPSD-755, Revision 01, "Reactor Coolant Pump Seal Failure Probability Given a Loss of Seal Injection," Combustion Engineering, Inc., May, 1988.

2. BNL Technical Report W6211-08/99, "Guidance Document for Modeling of RCP Seal Failures," Martinez-Guridi, G., et. al., August 1999.

3. Generic Issue 23, "Reactor Coolant Pump Seal Failure," October 1983.

4. Federal Register Notice 56 FR 16130, "Solicitation of Public Comment on Generic Issue 23, 'Reactor Coolant Pump Seal Failure' and Draft Regulatory Guide Issuance, Availability," April 19, 1991.

5. NRC Draft Guide DG -1008, Reactor Coolant Pump Seals, April 1991.

6. SECY-225, "Issuance of Proposed Rulemaking Package on GI-23, Reactor Coolant Pump Seal Failure," J. M. Taylor (NRC) to the Commissioners, August 26, 1994.

7. TM-0074, BW/IP N-9000 Instruction Manual for Millstone 2 BJ N-9000 Seal Cartridge.

8. ASME Steam Tables, American Society of Mechanical Engineers, 1967.

9. Advanced Light Water Reactor Utility Requirements Document: Volume II, ALWR Evolution Plant, Chapter 1, Appendix A: Key PRA Assumptions and Groundrules, EPRI, December 1993.

10. "Loss of Cooling Water to a Bingham Boiler Circulation Pump Mechanical Seal Demonstration Test at Alamitos Unit 3 (Pump Operating)," Procedure Number 2PE-211-02, Revision 0, San Onofre Nuclear Generating Station Unit 2, Retested on November 1, 1985.

11. 1729-400-003-00, "10 CFR 50.59 Evaluation of RCP Seal Retrofit at SONGS 2 & 3," O'Donnell & Associates, January 21, 1986.

12. E12.5.146, "Post-Test Inspection for Loss of Cooling test Performed on November 1, 1985," Bingham-Willamette Co., November 11, 1985. (Proprietary)

13. Kalsi Engineering, Inc., Report, "O-Ring Static Seal Performance Evaluation Under Loss of Component Cooling Water to Reactor Coolant Pump at SONGS Units 2 & 3," March 1986.

14. 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

15. GS-1543, "Loss of Component Cooling Water to the Reactor Coolant Pump Seal Cartridge on Hot Standby," Byron-Jackson Pump Division, November 1980.

16. GS-1520, "Report on Loss of Component Cooling Water to the Reactor Coolant Test on Nuclear Reactor Coolant Pump," Byron-Jackson Pump Division, April 1979.

17. TR-ESE-754, "Test Report for the Performance Test of a Byron Jackson Pump Seal Cartridge Under Simulated Plant Loss of Cooling Water Conditions," Combustion Engineering, Inc., May 1988.

18. "Southern California Edison Company Reactor Coolant Pump 10 CFR 50.59 Evaluation of RCP Seal Retrofit at SONGS Units 2 & 3," January 1986, O'Donnell & Associates, Inc.

19. "Reactor Cooling Pump Operating Guidelines, Byron Jackson Four Stage Mechanical Seal Cartridge Design," Borg Warner Industrial Products.

20. "Seal Flow and Leakage Retrofit Report for Reactor Coolant Pumps at the Palo Verde Nuclear Generating Station (SBP1 Seal Type RCR950-B3)," Sulzer Bingham Pumps, July 1996.

21. 40A0-9904, Revision 8, "Reactor Coolant Pump Emergencies," PVNGS.

22. NUREG/CR-5567, "PWR Dry Containment Issue Characteristics," Yang, J.W., August 1990.

23. CE-NPSD-657-P, "Potential for Pressurization of the Component Cooling Water System: NRC Information Notice 89-54," ABB, October 1991.

24. CRC Standard Mathematical Tables, 25th Edition, Beyer, W.H., CRC, pg. 537, 1974.

25. NUREG/CR-5496, "Evaluation of Loss of Offsite Power Events at Nuclear Power Plants: 1980-1996," Atwood, C.L., et. al., INEL, November 1998.

26. CENPD-201-A, "System 80 Reactor Pump Loss of Component Cooling Water Test," Combustion Engineering, Inc., January 1991.

27. 80-C2/PVP-28, "Loss of Component Cooling Water Capability of a PWR Reactor Coolant Pump," Phelps, R., et. al., presented at PVP Conference, San Francisco, August 12-15, 1980.

29. NUREG/CR-4639, "Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR)," W. J. Reece, B.G. Gilbert, and R.E. Richards, Idaho National Engineering Laboratory, September 1994.

This page intentionally blank.

APPENDIX A

Summary Descriptions of RCP Seal Designs used in CE NSSS Plants

APPENDIX A
TABLE OF CONTENTS

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-KSB RCPs at PVNGS require 75 gpm per pump for the high pressure cooler and 17 gpm for the interstage seal cooler. The cooling water flow rate to the seal cooling heat exchanger is not displayed on the control panel, 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 event. There are three different configurations of the RCP seal cooling heat exchangers installed in CE NSSS plants.

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

At Palisades and Ft. Calhoun, the seal cooling heat exchanger is 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. All component cooling water flows through the shell of the tube-in-shell heat exchanger and through an internal cooling jacket in the pump cover. An 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 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. Hot RCS fluid at a rate of 1 gpm flows upward through the annulus between the pump shaft and the pump cover where it mixes with the 40 gpm being recirculated by the recirculating impeller. 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 a tube-in-tube design 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. Hot RCS fluid at a rate of 1 gpm flows upward through the annulus between the pump shaft and the pump cover where 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 a shell-in-shell design in series between the RCS and the seal cartridge. The heat exchanger is located 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 flow 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

During normal operation of the sealing system, seal staging flow coils are used to create a pressure drop of about one third of the RCS pressure across each of the lower 3 stages. 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 BJ 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. The temperature of the controlled bleedoff flow will rise rapidly during a loss of coolant event, 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 BJ 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 replacement parts for the BJ/SU seals. The material for the rotating face rings in the original Byron-Jackson BJ/SU seals was titanium carbide. Tungsten carbide is used in the BJ N-9000 and Sulzer seals 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 BJ 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 Seal Design

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 as a unit, therefore, the vapor stage is installed and removed separately. The seal cartridge consists of four seal stages: 3 stages which reduce the fluid pressure of the controlled bleedoff flow, and the fourth stage which is the vapor stage. All 4 stages are identical in configuration. Each of the lower 3 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-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. The springs' load provides a greater percentage of the closing force at low operating pressures and becomes a significant part of the effective balance of the seal stages.

Rotating Seal Ring and Support Ring

An important feature of the Sulzer seal is the support concept for the rotating seal ring which allows the seal sleeve to deflect at a different rate than the rotating seal ring during temperature and pressure transients. 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.

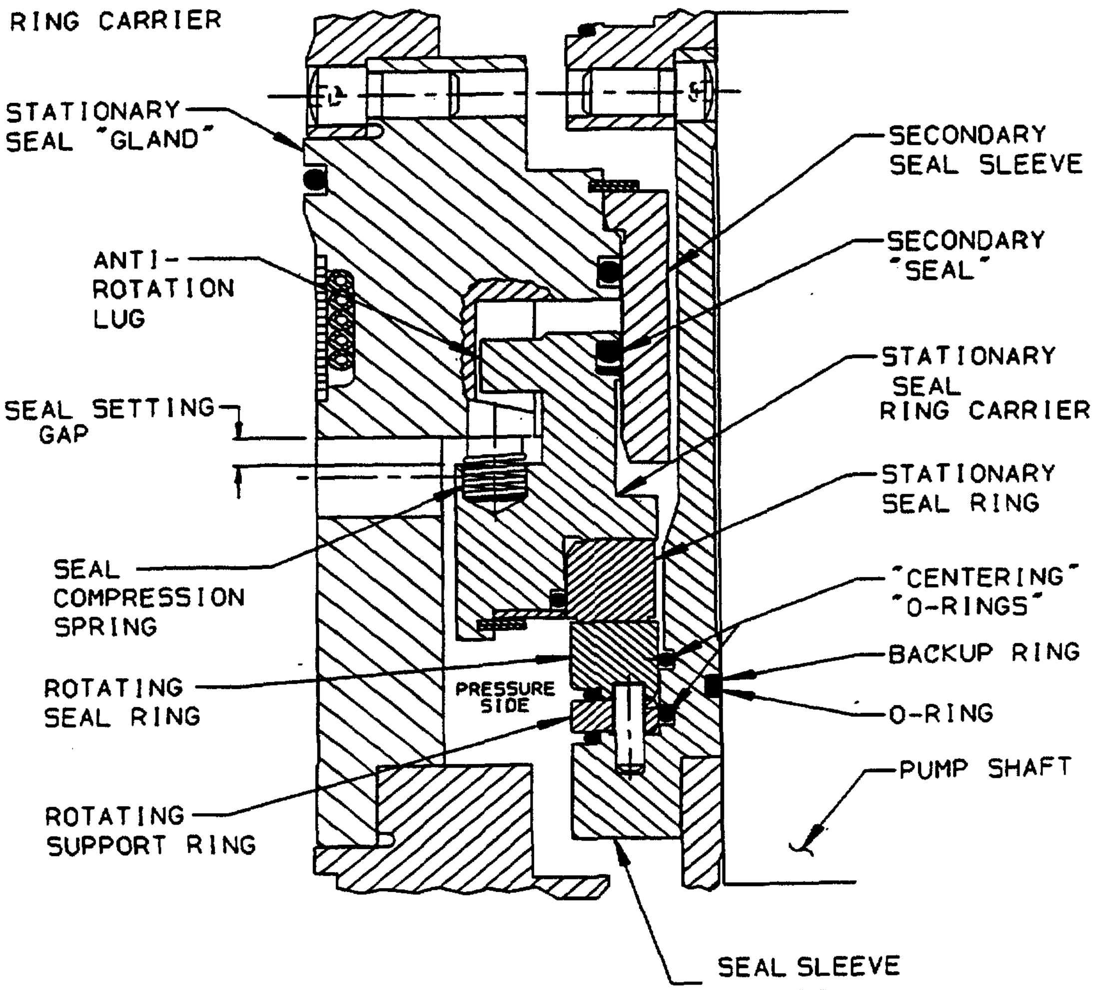
Seal Leakage

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 plant operating event. This confirms that the Sulzer seal design is capable of tolerating loss of seal cooling.

Seal Staging

Seal staging flow, 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 flow is a flow of 1, 1.5 or 3 gpm, depending on plant specifics, passing through the pressure breakdown devices. These devices are small diameter tubing whose length is selected to provide the correct pressure reduction at a plant specific CBO flow of between 1 and 3 gpm. Another important function of the staging flow is to cool the seals.

Figure A-1
Single Stage of a Sulzer Balanced Stator Seal Design



A.3 Sulzer 3-Stage Shaft Seal Design

The Sulzer seals at PVNGS are very similar to the Sulzer seals used at Calvert Cliffs and SONGS 2 & 3 in regard to the design of the stationary and rotating faces, carrier rings, elastomers, and seal sleeves. For this reason much of the description for the Sulzer seals in Section A.2 applies to PVNGS. However, the pressure breakdown devices (PBDs) at PVNGS are part of the pump and not part of the seal stage. The PBDs are also 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 by the PBDs and the throttling orifice at the CBO outlet, provides generous cooling to the seal faces. 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 Seal Design

The BJ N-9000 RC pump shaft sealing system consists of four BJ N-9000 mechanical seal stages 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 replaced as whole assemblies. At ANO-2, 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 Reactor Coolant System pressure. The fourth stage seal, also called the vapor stage, is replaced separately. The vapor seal normally operates at low pressure to minimize out-leakage 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 RCP idle and for a limited time with the RCP running. Figure A-2 presents the cross-section of a typical 4-stage BJ N-9000 seal assembly. Figure A-3 presents the cross-section of a seal assembly with three BJ N-9000 stages and a BJ/SU vapor stage such as is used at Waterford 3.

Stationary face configuration

The one-component configuration of the BJ 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 shows the BJ N-9000 rotating face and holder assembly assembly. The single component configuration of the rotating face eliminates any frictional hysteresis effects which are 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 BJ 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 BJ 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 BJ 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 axi-symmetric 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 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 is equally applicable to the original SU seal cartridge design. The physical parts arrangement is quite different in the BJ N-9000 seal in comparison to the BJ/SU seal. (See Figure A-4). A major change in the BJ N-9000 design is the improvement in the seal face ring deflection control. Hydrodynamic operating principles apply to both the BJ N-9000 and the original BJ/SU seal designs. However, the improvements made in deflection control for the BJ N-9000 seal design will result in repeatable and predictable behavior with greater tolerance for operational transients.

Figure A-2
Cross-Section of a 4-Stage BJ N-9000 Seal Assembly

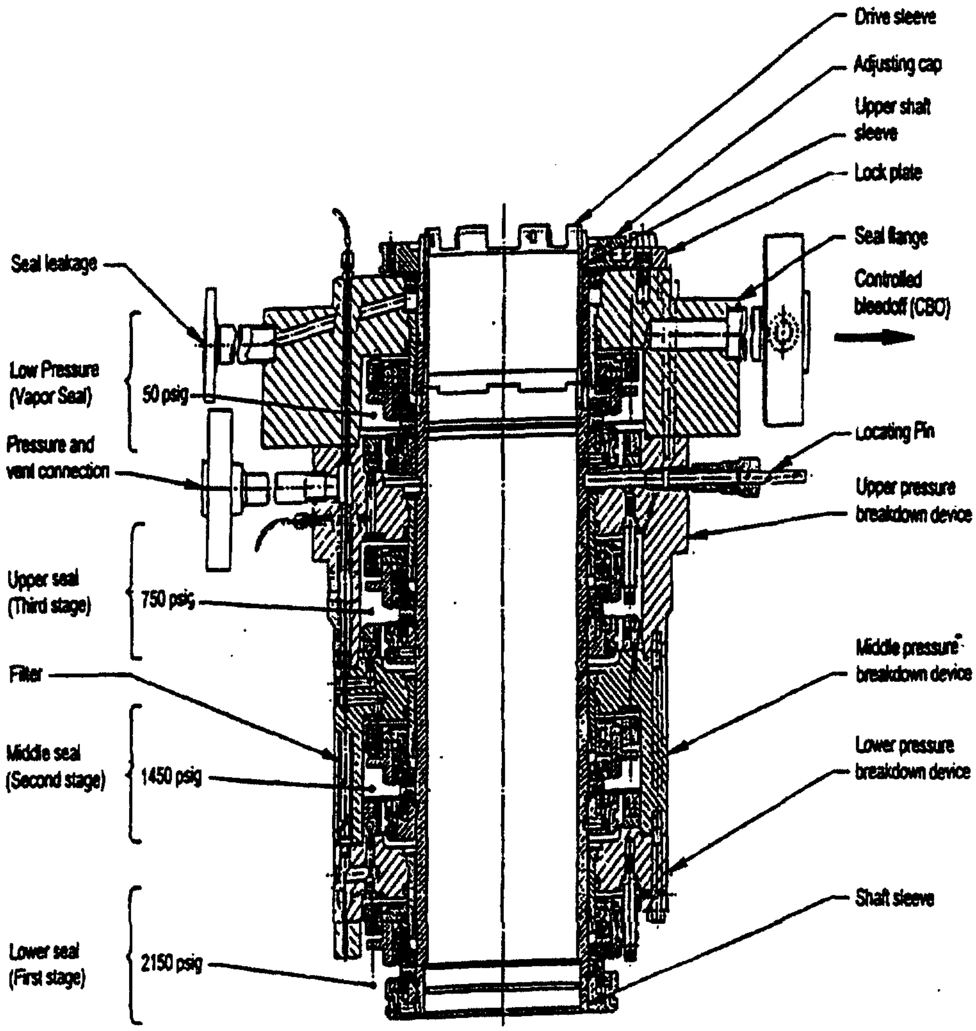


Figure A-3
Cross-Section of a 3-Stage BJ N-9000 Seal Assembly with a BJ/SU Vapor Stage (used at Waterford 3)

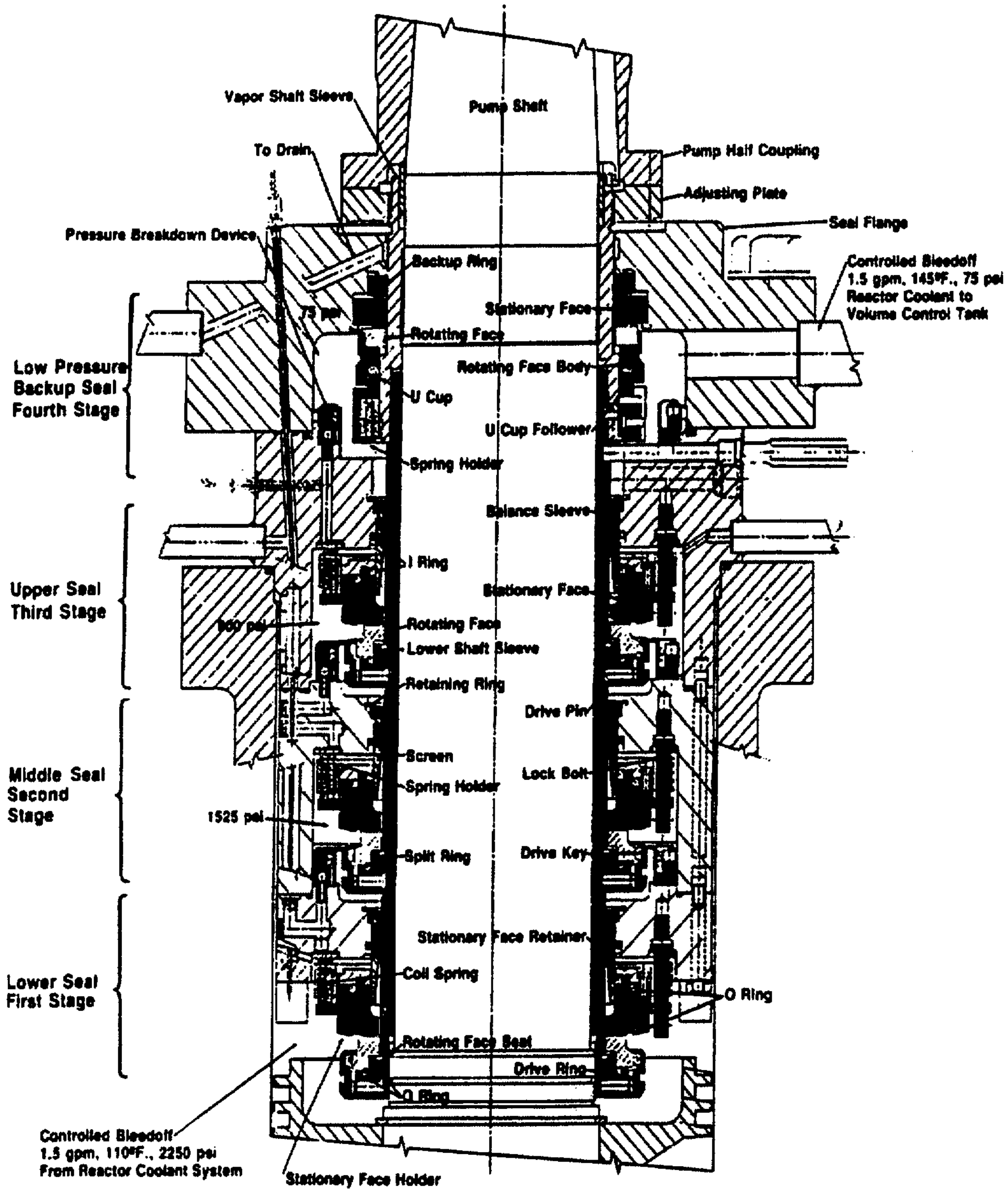
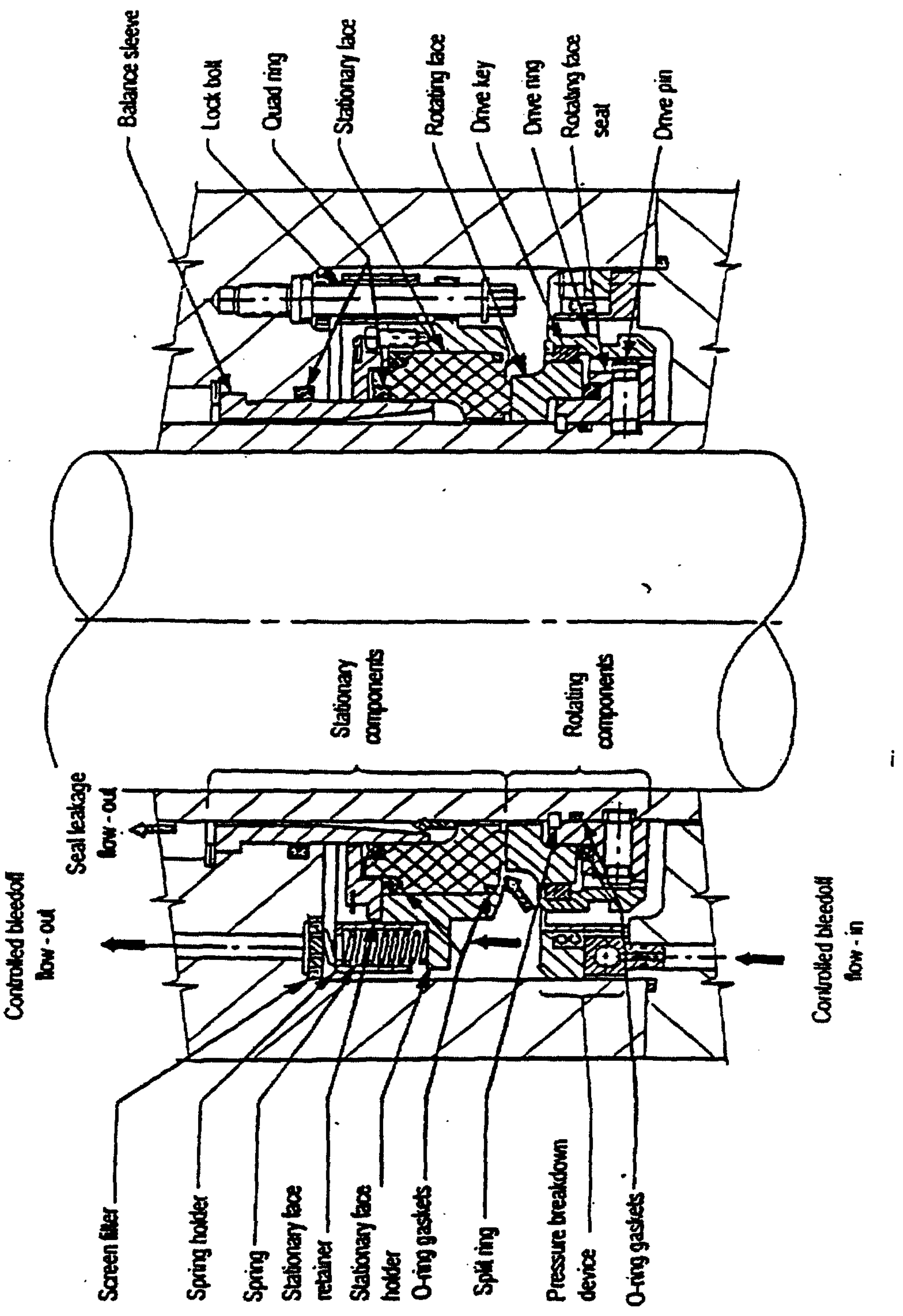


Figure A-4
BJ N-9000 Seal Rotating Face and Holder Assembly



A.5 Byron Jackson SU Seal Design

Description of Seal Cartridge

The BJ/SU seal cartridge uses four face-type hydrodynamic mechanical seals. The uppermost vapor stage seal 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. At normal operating conditions, the pump suction pressure is 2150 psia, and the vapor stage seal cavity pressure is about 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 stage seal would be 2150 psig, 1450 in the second stage seal cavity, 750 psig in the third stage seal cavity, and 50 psig in the vapor stage seal cavity. At these pressures the flow rate through the PBDs is designed to be 1 gpm. 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 presents a cross-section of a 4-stage BJ/SU seal. Figure A-6 presents a more detailed cross-section of a single BJ/SU seal stage.

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 frictional heat and wear. At the same time, the full system pressure would be imposed across the vapor stage 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.

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 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 are the design originally supplied with the RCPs. Ft Calhoun was the last CE NSSS plant using the BJ/SU RCP seals. Fort Calhoun replaced these seals with the BJ N-7500 during their June 2002 refueling outage. BJ N-7500 seals are BJ N-9000 seals with a smaller inner diameter to match the Fort Calhoun RCP shaft diameter.

Figure A-5
Cross-section of a 4-Stage BJ/SU Pump Seal

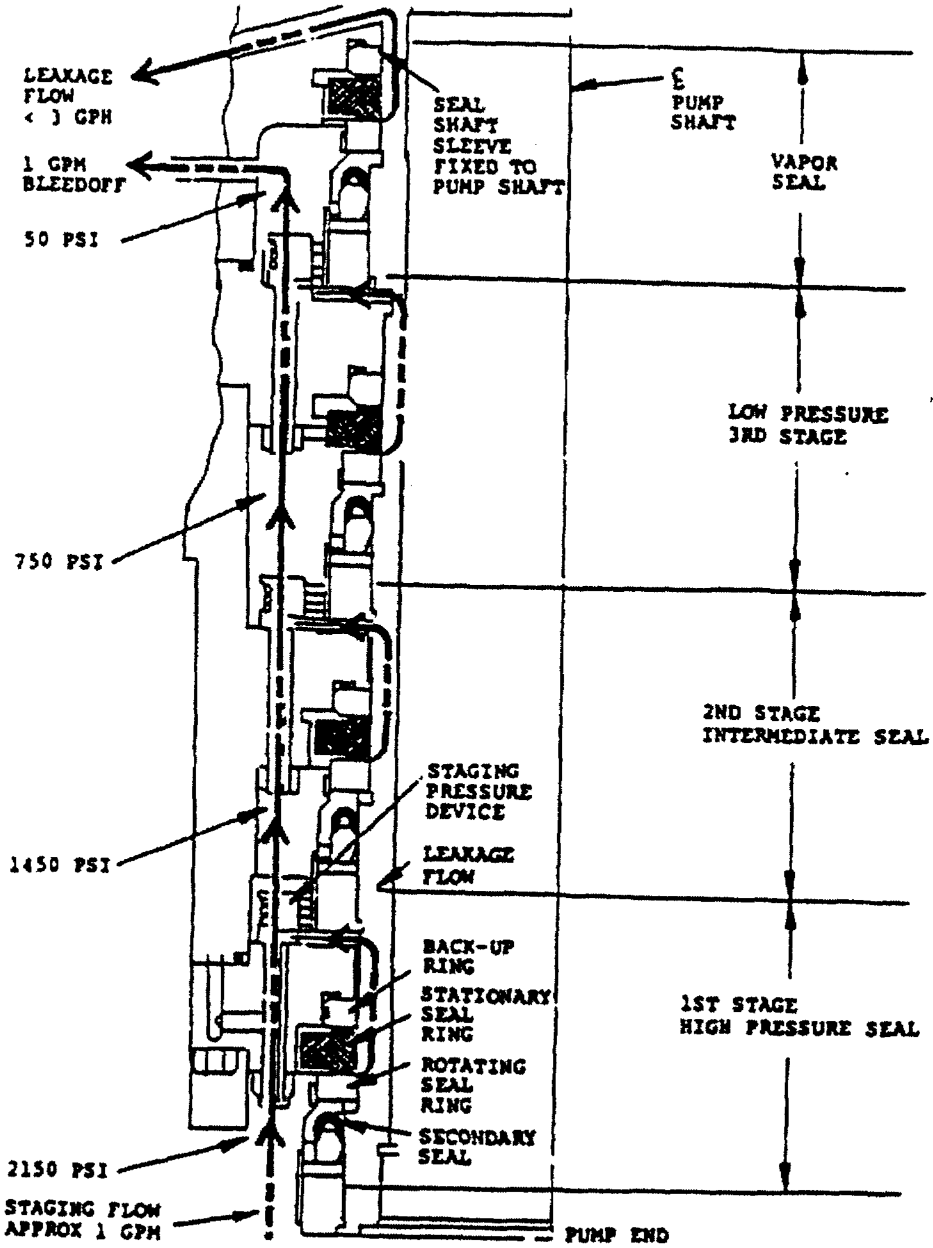
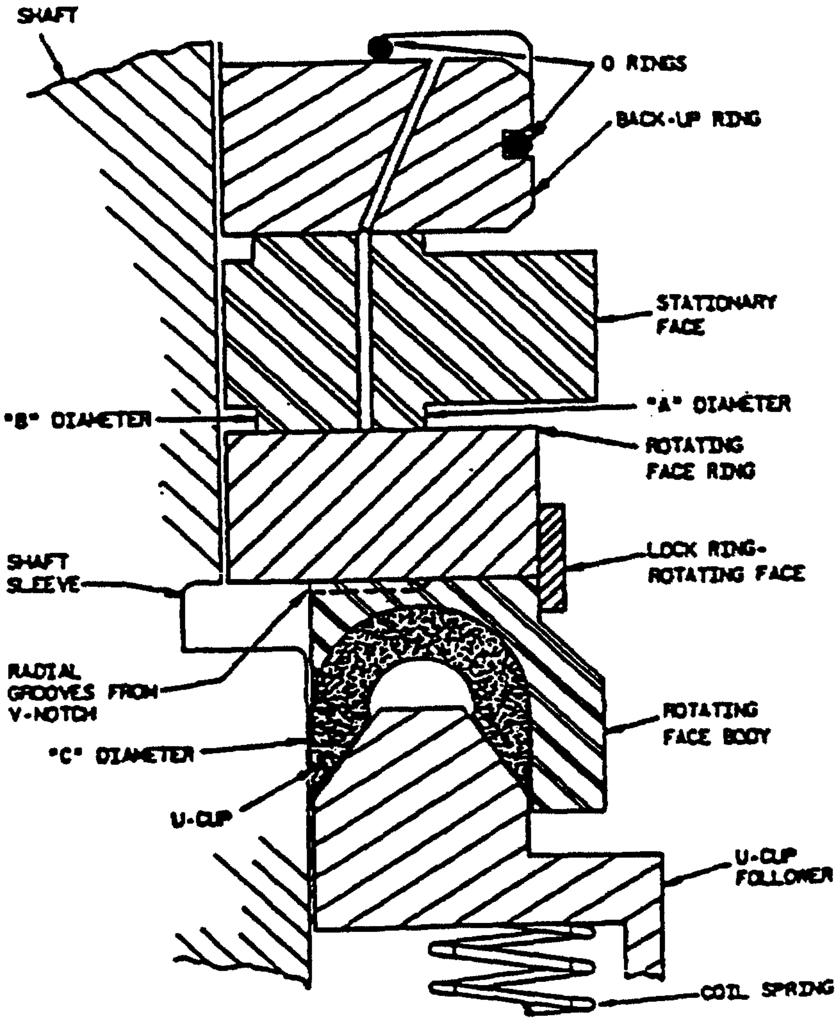


Figure A-6
Cross-section of a Single BJ/SU Seal Stage



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

This page intentionally blank.

APPENDIX B

Responses to NRC Requests for Additional Information Concerning CE NPSD-1199P, Revision 0

INTRODUCTION

Appendix B provides responses to NRC Requests for Additional Information (RAI) issued in August 2001 and July 2003. Responses to these RAIs are contained in Sections B.1 and B.2 respectively. References cited are shown in Section B.3.

B.1 Response to NRC Request For Additional Information Concerning CE NPSD-1199, Rev 0, "Model for Failure of RCP Seals Given Loss of Seal Cooling, Dated August 17, 2001

RAI 1.1

Section 3.4 (pg. 3-11 ¶ 2) states that the Kalsi Engineering Tests clearly indicates a high likelihood of high temperature elastomer survivability for periods in excess of eight hours. In addition, Section 5.3.1 (pg. 5-5 ¶ 3) states that "closure of the CBO (controlled bleedoff) line will stop flow through the seal PBDs (pressure breakdown devices) and equalize the seal cavity pressures at the level of the RCS (reactor coolant system) pressure (approximately 1000 - 1200 psia). The RCS temperature ... will be about 500 to 540°F." However, the test failure data points provided in Figure 3.4-1 (pg. 3-12) and discussed in Section 7.3.1 (pg. 7-8 ¶ 5) indicate failures within the first few hours at very high exposure temperatures (i.e. greater than 550°F). Please clarify either how the very high exposure temperature test data points (and if there is any high pressure data) have been used in developing the RCP seal failure model and their associated failure probabilities or justify why these temperatures and/or pressures cannot be reached during any accident scenarios. Also, please provide the basis for the ranges of temperatures and pressures that are considered.

RAI 1.1 Response

The Kalsi tests subjected static sealing O-rings to high temperatures with a differential pressure of 2250 psig (Reference B1.1). These seals were prototypical of those seals and seal installation used in the Bingham-Willamette Company's mechanical seal package. They are similar to that used by Byron Jackson in the N-9000 RCP seal design. The intent of these experiments was to determine the extent to which the elastomer seal performance would be affected when exposed to high temperature and pressure. The temperature exposure tests were conducted at 550°F, 600°F and 650°F.

Only two seal failures occurred during the test program. Both seal failures occurred when exposed to a 650°F environment (cf., Figure 3.4-1). All other seals indicated satisfactory performance for the duration an eight-hour test with no measurable leakage. These points were included in the figure as "open" symbols (that is, no failure).

One of the two data points from the BJ N-9000 test (Reference B1.2) was shaded incorrectly. This point represents a non-failure condition. The pressure drop across these seal stages varied during the test dependent upon seal location and status of CBO. Additional data points associated with the ethylene-propylene O-rings used in the BJ/SU seals have been added to Figure 3.4-1 for completeness. These O-rings successfully operated during conditions typical of a SBO with CBO operational. Elastomers in the lower three stages were exposed to temperatures in excess of 500°F and one stage was exposed to temperatures of about 400°F. Elastomers lasted for more than 40 hours. Pressure drops across these seals varied from about 400 to 1000 psig (Reference B1.3).

One O-ring failure was incorrectly included in Figure 3.4-1. The failure occurred in a small O-ring on the non-rotating face of the upper seal and was due to non-homogeneity in the material resulting from the manufacturing process that has since been refined. The O-ring that failed was constructed from a straight piece of material with the ends bonded together. The bonded region was the O-ring weak point. Current techniques form the O-ring as an integrated unit. This O-ring was identified as the weak point in the N-9000 seal. Other N-9000 elastomers were intact throughout the test and maintained their sealing integrity. (It should also be noted that the failure occurred at a temperature of 500°F, not 350°F as shown in the original figure.) This data point has been removed in the updated Figure 3.4-1.

Not included in the above figures are results of AECL tests for a Bingham Secondary Seal based on a mounting with both 0.009" and 0.018" diametrical clearances (Table 3 of Reference B1.4). This data included 24-hour high temperature and pressure exposure of the O-rings. Pressure temperature combinations included three tests at 2200 psid and 550°F. Results of these tests also indicated no secondary seal leakage and minimal change in elastomer hardness. Some extrusion was noted, with the length of the extruded material varying from a maximum of 0.02" for the 0.009" tests to 0.1" for the 0.018" clearance test. Typical SBO diametrical gap clearances for the secondary seals for N-9000 and Sulzer seals are about 0.004" and 0.006" respectively. Reference B1.4 also indicated that BJ static O-rings (such as those used in BJ/SU seals) are expected to function during Station Blackout conditions.

A review of operational loss of seal cooling events supports the conclusions that, with the exception of Nitrile U Cup elastomers utilized in the BJ/SU designs, gasket failures have not contributed to excessive seal leakage. Several instances exist where prolonged RCP seal exposures (six to nine hours) to high temperatures degraded the Nitrile U-cup on the lower seal stage and caused a first stage failure for one event. This conclusion is consistent with Reference B1.4, which found that the most likely mechanism to cause high leakage through the Byron Jackson BJ/SU seal assembly is hardening of the U-cups.

Late in an SBO event [[ ]]^{a,c}, RCS cold leg temperatures and pressures will be near the saturation temperature for the SG setpoint pressure. This in the range of [[ ]]^{a,c} (plant specific) for CE designed PWRs. Additional detail on the plant response during an SBO is included in the Response to RAI 1.2.

Test data and operational experience confirms that the EP elastomers used for secondary seals and static sealing in the BJ/SU, N-9000 and Bingham RCP seals are capable of operating in a station blackout environment. The worst case pressure condition for extrusion for these seals occurs in the vapor stage when CBO is isolated. Under that condition the RCP seal vapor stage (or last stage) is required to hold full RCS pressure. Given early CBO isolation, [[ ]]^{a,c} the vapor seal temperature would be expected to be approximately [[ ]]^{a,c}. Even if CBO were not isolated, BJ/SU tests indicate that the vapor seal temperature would be approximately [[ ]]^{a,c}. Thus, when a vapor stage seal arrangement is used, the temperature in that region would be well below [[ ]]^{a,c} and failure of a vapor stage operating in this temperature regime is unlikely.

The probability of elastomer failure has been re-calculated based on the reassessment of the data as discussed in the responses to RAI 1.7 and RAI 1.8. Data used in this calculation include results of the Kalsi experiments and observations from loss of seal cooling events at CE PWRs. The revised Table 9.2-1 is provided in the response to RAI 1.18. Furthermore, Tables 9.2-2 through 9.2-10 have been added to identify the elastomer failure probabilities used for each set of RCS conditions.

RAI 1.2

Section 4.2.3 (pg. 4-16) discusses hydraulic instability (i.e. the pop-open failure mode) and states that the face seal will remain stable if one of two conditions occur; inlet fluid is sufficiently subcooled (i.e. greater than 50°F) or back-pressure acting on the seal is greater than half the saturation pressure at the inlet temperature. This is consistent with NUREG/CR-4821. However, only the subcooling condition is discussed and relied upon throughout the rest of the topical report, which leads to a number of plant-specific questions. These questions are with regard to how plants assure there is adequate subcooling when (1) the majority of plant procedures do not require this amount of subcooling and (2) it is not clear if sufficient subcooling at the seal entrances is achievable under all conditions and is within the control of the operators. The representative post-accident conditions may not be achievable (e.g. pg. 5-6 for Station Blackout (SBO) events and pg. 5-10 for Loss of Component Cooling Water (LOCCW) events). Moreover, it may not even be possible to maintain the RCS 50°F subcooled for either the SBO or the LOCCW conditions. For SBO conditions, it is not possible to maintain coolant level on cooldown because charging is not available and because of coolant shrink and RCS fluid losses. The same is true for LOCCW if the charging pumps depend on Component Cooling Water (CCW). Consequently, pressure control may not be possible, and it may not be possible to maintain 50°F subcooling in the RCS and at the inlet to the first stage RCP seal. Thus, there is a possibility the first seal stage may pop-open, if the backpressure on the first seal stage is less than one-half the stage inlet saturation temperature. The topical report needs to address and reflect in its modeling considerations the potential for sufficient backpressure to exist to maintain the face seal stable.

In addition, the statement made in Section 5.3.1 (pg. 5-5 ¶ 2) that Emergency Operating Procedures (EOPs) instruct operators to maintain the plant in a stable condition with RCS subcooling between 20 and 50°F may be misleading and is inconsistent with the parenthetical statement that procedures only require a minimum of 20°F (pg. 5-8 ¶ 2). Because the RCP seal failure model relies on greater than 50°F subcooling for success, those plants whose EOPs allow RCS subcooling to be less than 50°F must be considered to have a high likelihood of not having adequate subcooling, unless it can be shown that such conditions cannot occur phenomenologically. Per Table 5.3-3 (pg. 5-9) all Combustion Engineering (CE) plants for SBO events have lower subcooling requirements. For these plants and for almost all plants under SBO conditions, the RCP seal failure model could be simplified, if the back-pressure is shown to be inadequate, by assuming inadequate subcooling under these conditions. Otherwise, a justification needs to be provided that demonstrates (1) that the plants will always have 50°F subcooling at the RCP seal inlets even though procedures allow less, or (2) that there is always sufficient back-pressure under conditions in which subcooling cannot be assured.

RAI 1.2 Response

The response to the question will be divided into three parts. First is a discussion of the use of the 50°F subcooling criterion. Test data will be used to demonstrate the robustness of the seal operation under various high pressure - low subcooling conditions. Secondly, additional information is provided regarding the SBO temperature transient. Finally, the role of the EOPs and operator actions are discussed along with current CEOG intentions to enhance the clarity of the EOPs for operation with complete loss of seal cooling.

Selection of 50°F Subcooling Criterion

The use of the 50°F subcooling criteria alone is conservative. This criterion is sufficient to ensure seal stability. As was noted in the question, when the liquid entering the seal is not subcooled by 50°F, flashing may be significantly abated by increasing the downstream pressure to greater than 50% of the upstream pressure. This feature was not considered when investigating pop-open seal failures for cases where CBO was not isolated. This is conservative as certain opportunistic failures may improve seal stability of downstream seal stages. For example, failure of the second seal stage would increase the pressure on the third stage and hence make it less likely to pop-open. Instead the model assumes that the most likely seal failure would occur first (third stage in the four stage model).

The backpressure issue was included tacitly in the model in the treatment of CBO isolation. CBO isolation will eliminate the pressure breakdown function of the pressure breakdown devices (PBDs) and de-stage the seals. Thus the RCS pressure will be applied to all stages. This in effect removes the seal pressure drop and via the second criteria will consequently stabilize all seals with the exception of the last stage or vapor seal.

The ability of the seal stages to withstand a range of pressures and temperatures without pop-open or significant leakage can be established by investigating the last stage seal performance in the BJ/SU SBO and N-9000 SBO tests. Data from the BJ/SU SBO tests are presented in the attached Figures B1.2-1, B1.2-2 and B1.2-3 (from Reference B1.3). The test consists of a long duration exposure (40 to 70 hrs) of a BJ/SU seal to SBO conditions. The seal is static and the test facility is pressurized to 2200 psia and maintained at 540°F. CBO is operational throughout this test. Subcooling of the vapor stage can be seen to vary from a low of about 30°F to a high of over 100°F (see Figure B1.2-4). The pressure drop across the seal varied from a nominal value of 150 psid to about 650 psid. At no time during the test did seal leakage exceed 0.3 gpm. Thus, for this range of conditions, no pop-open was observed nor was there any significant bistable regime.

The BJ/SU test did note some quasi-static behavior of the third seal stage. This stage appeared to partially open and lost some pressure retention capability. It is estimated that the seal stage face leakage during the interval was about 0.5 gpm and was controlled by the vapor stage. In no instance did the third seal behavior propagate upstream to either the lower or middle seal stages.

The N-9000 test investigated the ability of the advanced BJ seal (without a vapor stage) to withstand a simulated station blackout. The test was conducted for eight hours and consisted of a heatup phase, followed by loss of seal cooling. The CBO was maintained for a period of 30 minutes, allowing the RCP seal chambers to heatup to about 550°F. At 30 minutes, the CBO was isolated, the seals de-staged and full system pressure was taken across the last seal stage. Without the CBO flow, the upper stage RCP seal temperatures fell to about 500°F. This resulted in a condition where the last seal stage (upper seal) was exposed to a temperature of 500°F and a stage pressure differential that varied from about 1680 to 2400 psid; stage subcooling varied from 55°F to 130°F. During the test, the upper stage seal operated without any pop-open or bistable behavior. The seal leakage was maintained at 0.04 gpm throughout the event. The test was terminated due to failure of a static O-ring in the upper seal stage; failure was caused by an inhomogeneous O-ring bond, although the elastomer material itself was flexible and showed minimal extrusion. This seal stage connects the upper seal stage with the ambient pressure chamber, thus the leakage pressurized the low pressure region of that stage and leaked through a small hole in the stationary face of the seal to the leakage collection chamber. The hole, intended as a pressure balancing measure to minimize face deflections, limited the outflow to near CBO conditions. The impact of the failure was primarily to re-stage the seals. This seal was predicted to be the weakest link in the component. The seal is no longer made from a bonded strip but is now integral and capable of extended high temperature performance.

The key features of the N-9000 tests were:

1. Pop-open behavior was not observed even though subcooling reached 55°F.
2. Bistable behavior was not noted even though pressure differentials exceeded 2200 psid.
3. Failure of the limiting static O-ring had minimal impact on leakage. However, failure of the uppermost O-ring would re-stage the seals since the pressure-balancing hole provides a leak path to the environment.
4. All elastomer materials performed well during the 8 hour test.

Station Blackout Scenarios

The ability to control subcooling is limited for the SBO event. Analyses of SBO events have been performed for two representative CE PWRs (FCS and a typical 3410 Mwt plant) using the CE Nuclear Transient Simulation Code (Reference B1.5). CENTS is a code originally developed for use in nuclear plant simulators and is used for both best estimate and design analyses. CENTS analyses provide realistic post-SBO plant responses; results of the analyses are presented in Figures B1.2-5 through B1.2-11. The analyses indicate that, without operator action, the SBO event will maintain the RCS with a greater than 50°F subcooling for a period of [[ ]]^{a,c}. The high subcooling is a result of residual hot water in the pressurizer and the approximate 20°F hot leg-cold leg temperature difference that exists during the early natural circulation time period. Such temperature differences have been confirmed through natural circulation testing at SONGS.

In the SBO event considered above, the turbine driven AFW was considered available for the duration of the event. For situations with CBO isolated, the lower seal would lose subcooling first. However, since the seal pressure would be high at all seal stages, pop-open failures would be averted. The last or vapor seal is further protected against pop-open by the lower operational temperatures, ensuring adequate subcooling. It should be noted that since it takes more than three hours for the lowest seal to reach pop-open subcooling levels and since CBO closure removes pressure drops across all seals, save the last one, CBO isolation even late in the scenario would also prevent pop-open failure.

Operator Actions and CEN-152

Loss of CCW events allow control of plant subcooling primarily via use of pressurizer heaters and charging. CE NSSS designs utilize positive displacement charging pumps without any dependency on CCW, thus, operator actions to control subcooling are readily accomplished. Currently, plant specific procedures for responding to a loss of CCW and CEN-152 (Reference B1.9) require that a minimum of 20°F subcooling be maintained in the hot leg during the event. Anecdotal evidence suggests that while a minimum subcooling of 20°F is required by procedure, plant operators routinely maintain subcooling margins in excess of 50°F. CEOG plants recognize the significance of higher level of subcooling, therefore such subcooling will be reflected in plant specific analyses.

Figure B1.2-1

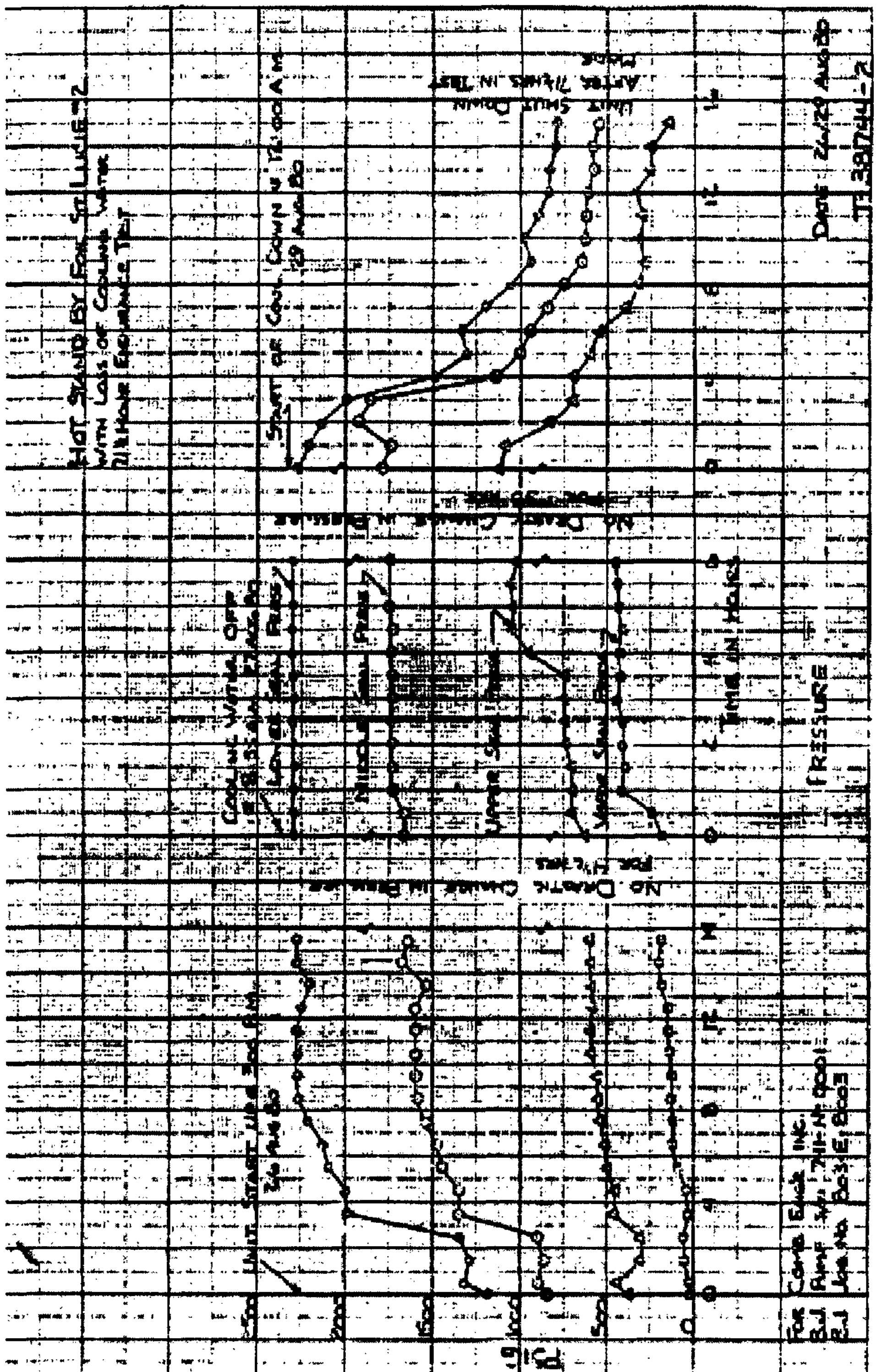


Figure B1.2-2

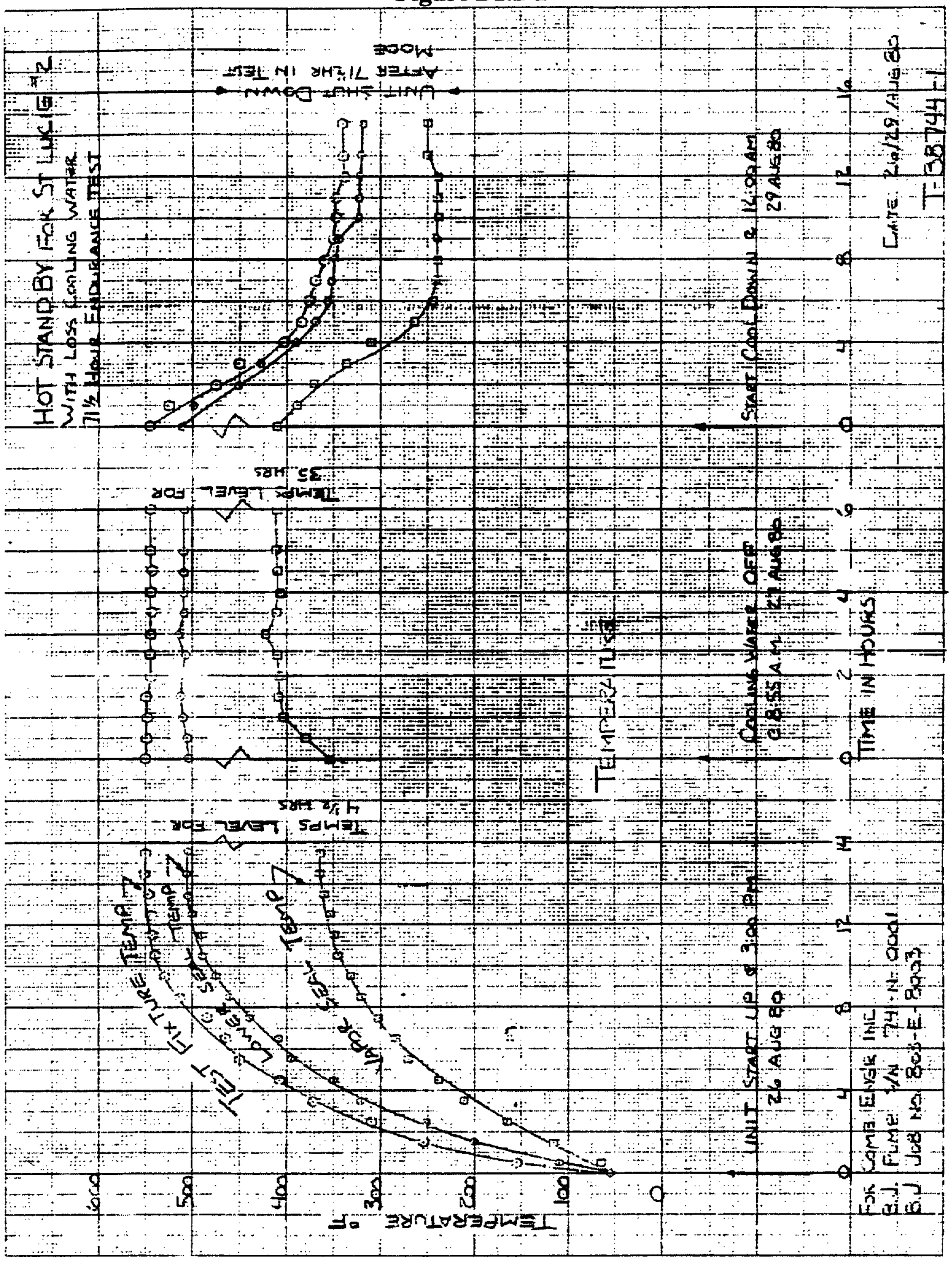

HOT STAND BY FOR ST LUCIE #2
WITH LOSS COOLING WATER
71½ HOUR ENDURANCE TEST
UNIT SHUT DOWN
AFTER 71½ HR IN TEST
MODE
TEMPERATURE °F
TIME IN HOURS
T-38744-1

Figure B1.2-3

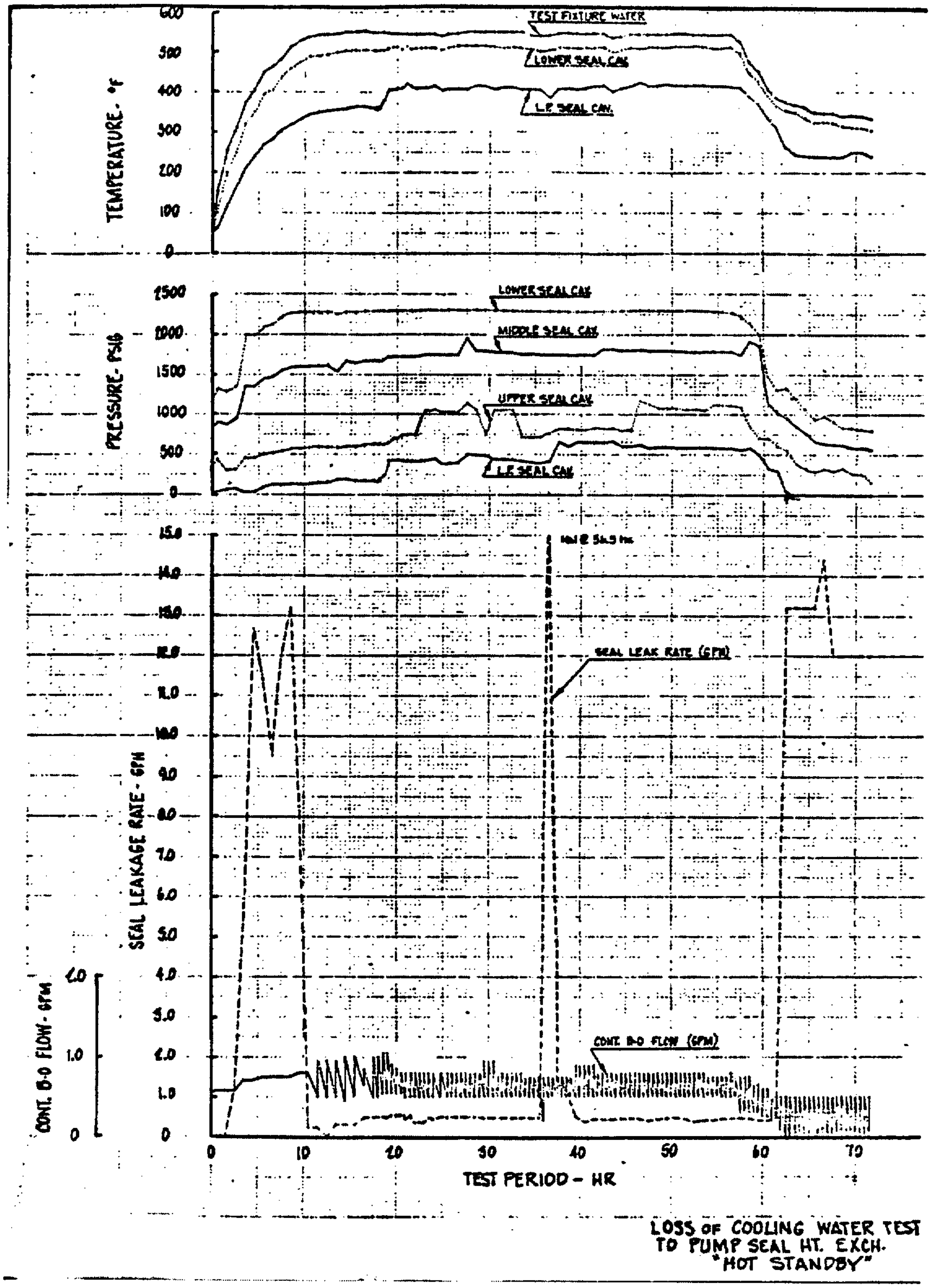

TEMPERATURE - °F
TEST FIXTURE WATER
LOWER SEAL CAV.
L.P. SEAL CAV.
PRESSURE - PSIG
LOWER SEAL CAV.
MIDDLE SEAL CAV.
UPPER SEAL CAV.
L.P. SEAL CAV.
SEAL LEAKAGE RATE - GPM
SEAL LEAK RATE (GPM)
CONT. B-O FLOW - GPM
CONT. B-O FLOW (GPM)
TEST PERIOD - HR
LOSS OF COOLING WATER TEST
TO PUMP SEAL HT. EXCH.
"HOT STANDBY"

Figure B1.2-4: Vapor Stage Subcooling During BJ/SU SBO Test

a, c

Figure B1.2-5: BJ/SU SBO Test: Vapor Stage Seal Leakage

a, c

Figure B1.2-6: FCS Station Blackout: No Operator Action

a, c

Figure B1.2-7: FCS Station Blackout: No Operator Action
Hot Leg Temperature vs. Time

a, c

Figure B1.2-8: FCS Blackout, No Operator Action
Hot Leg and Cold Leg Subcooling

a,c

Figure B1.2-9: Station Blackout: RCS Pressure, 3410 Mwt

Figure B1.2-10: Station Blackout: Hot Leg Temperature: 3410 Mwt

a, c

Figure B1.2-11: Station Blackout: Subcooling in Hot and Cold Leg: 3410 Mwt

a, c

RAI 1.3

The topical report makes statements (pg. 4-7 ¶ 1) regarding the potential success or failure of Byron Jackson (BJ) or Bingham Willamette Company (BWC) (now Sulzer) static and secondary seals based on results from tests or calculations made by the contractors to the U.S. Nuclear Regulatory Commission (NRC), which were developed based on limited information, testing, and available materials without the cooperation of either the owners group or the pump manufacturer and should not be taken as definitive results. The topical report must justify the expected performance and failure potentials based on the available information from industry experience, tests, and manufacturer data. Please provide justifications for seal performance assertions based on CEOG and/or RCP seal vendor tests or calculations, including in particular more detail regarding the results of the RCP seal testing and/or analyses that have been performed for BJ and Sulzer seal cartridges (e.g. BJ LOCCW test at St. Lucie and the BJ N-9000 SBO test). Please include a description of how these results are reflected in the model and/or failure data.

Examples of performance claims and conclusions that need further supporting experiential information, analyses, modeling, or test results include:

1. *The statement (pg. 4-6 ¶ 3) that the current BJ and BWC seal designs have superior temperature performance and are consistent with the Brookhaven National Laboratory (BNL) qualified O-rings.*

RAI 1.3.1 Response: With the exception of the Nitrile U-cups in the early BJ/SU seal designs, BJ and BWC have used ethylene-propylene elastomers in the static secondary seals. Elastomer seals of this type were identified as "qualified" in Reference B1.6. Tests of prototypical BJ and BWC ethylene-propylene seal designs have been performed in References B1.1, B1.2 and B1.3. The Kalsi tests included full pressure (2250 psig) and high temperature 550°F, 600°F and 650°F experiments. The 550°F and 600°F tests indicated no measurable leakage for a period of 8 hours. The tests were terminated at this point. A subsequent seal inspection indicated that seals exposed to 550°F temperatures exhibited no signs of guminess or embrittlement and a small extrusion lip was noticed. The 600°F post-test inspection indicated that the O-rings remained elastic and there was no embrittlement or guminess of the material. During the last four hours of the experiment there was a slight drop in pressure across one of the two seals tested (2300 psig to 2200 psig). The drop was attributed to a small amount of extrusion which resulted in a small increase in the seal cavity volume. Additional information on seal performance may be inferred from prototype loss of CCW tests conducted with the BJ/SU and N-9000 seals; these tests confirm the robustness of ethylene-propylene seals to successfully operate in a high temperature environment. In the BJ/SU test, the O-rings successfully operated in a 500°F to 520°F environment with pressure drop of between 500 and 1000 psid for a period in excess of 40 hours (Reference B1.3). Similarly, the N-9000 SBO test indicated successful ethylene-propylene elastomer performance when exposed to high temperature and pressure environments. Since the RCS cold side temperature is limited to a maximum value of 540°F to 565°F (plant specific), these test results support the robustness and low expected failure probability selected for the static ethylene-propylene elastomers.

2. *The statement (pg. 4-7 ¶ 2) that failure of qualified O-rings is unlikely during a Loss of Seal Cooling (LOSC) event, which seems inconsistent with the prior paragraph in the topical report that states one O-ring in each stage of a Sulzer seal assembly is susceptible to significant extrusion failure if subjected to full system pressure during a LOSC event. Note that this statement refers to O-rings that have been tested at specific temperatures, gaps, and pressure differentials expected during a LOSC event. These tests relate to Westinghouse RCP seal and O-ring materials. No O-ring material was qualified for "full" system pressure across a single seal stage by these tests.*

RAI 1.3.2 Response: The secondary seal elastomer tests presented in Appendix A of Reference B1.4 included experiments on BJ U-cups and Bingham International O-ring arrangements subject to both normal operation (750 psig) and (2200 psig) to pressure loads. These tests were performed by the contractors to the U.S. Nuclear Regulatory Commission (NRC), without the cooperation of either the owners group or the pump manufacturer. It was further noted that these results should not be taken as definitive results. However, AECL did indicate that the U-cup test was considered "worst-case" conditions (Reference B1.4). Findings of U-cup deterioration were similar to that observed in BJ tests and operational events involving the BJ/SU seals. O-ring tests used reasonable (0.009" and 0.018") diametrical gaps and representative materials. While these were not prototypical, the diametrical gaps used bound the BJ seal design. The conclusion that the seals could support high temperature exposure was based on the results of prototype experiments described in response to RAI 1.1 and the response to RAI 1.3.1.

3. *The conclusion of Section 4.2.3 (pg. 4-17) that the use of improved materials has reduced the potential for significant seal face flaws and thus the potential for a pop-open event.*

RAI 1.3.3 Response: The new generation of RCP seals has been designed to improve seal performance for design and off-design conditions. These designs have focused on improving elastomer temperature response, minimizing frictional resistance of gasket seals, and carefully accounting for the effects of thermal expansion. In addition, for N-9000 seals, pressure induced seal face deflections have been eliminated by the inclusion of pressure balancing holes through the face of the seal. The net impact of these changes have been to improve the thermal performance of the seal secondary elastomers by eliminating the use of Nitrile U-cups and by increasing the stability of the seals by minimizing thermal and pressure induced face seal deflections. Finite element analyses of the N-9000 seal design indicate that during a station blackout with the seal in a static condition, the primary sealing surfaces would tend to be divergent, thereby preventing leakage. The designer's concluded that the seal would be "safe in station blackout conditions and not be likely to pop-open" (Reference B1.8).

4. *The vapor stage temperature for the CBO-not-isolated case (pp. 5-10 and 5-11), which is nearly 100°F below the test results identified in Section 7.1.1 (pg. 7-2, ¶ 4).*

RAI 1.3.4 Response: Tables 5.3-4a, 5.3-4b, 5.3-4c, 5.3-5a, 5.3-5b, and 5.3-5c on pages 5-10 and 5-11 of CE NPSD-1199-P are representative of the seal package temperature distributions. The first two columns on each table represent the case when CBO is isolated approximately 10 minutes after loss of seal cooling. Stage temperatures are established based on experimental observations (See attached Figures B1.2-2, B1.2-3 and B1.3-1). CBO isolation imposes a constant pressure across all the seal stages. The low seal temperatures and high seal pressures ensure high subcooling at each seal location.

Columns 5 and 6 on each table represent the case where CBO is not isolated. Under this condition, the seal is staged. That is, the CBO flow creates a near equal pressure drop across each seal stage except the last one. For a four stage seal, each seal stage has a pressure drop of about 700 psid. The last stage is connected to the low pressure Volume Control Tank.

It is assumed that the pressure in the last stage was 70 psia. When the RCS pressure is 2200 psia, the actual pressure drops across each seal stage is about 700 psid. The temperature distribution was based on assuming a "near" adiabatic flow of RCS liquid through the seal stages. As a result of the high pressure on the lower stages, the fluid in the two lower most seal cavities would be highly subcooled. The third stage temperature is near saturation with saturation conditions existing in the vapor stage. The presence of a saturated vapor stage has been confirmed in the BJ/SU and N-9000 tests.

Columns 3 and 4 represent a delayed isolation of CBO. The temperature distribution reflects subcooled liquid conditions in all seal cavities at the time the seal package was isolated. The vapor stage temperature is assumed to be ~ 400°F. This is based on observations that equilibrium temperatures during the BJ/SO tests were in the 400°F range. So long as isolation results in seal package pressures in excess of about 250 psi, the liquid would be subcooled.

Three prototype experiments have been performed for loss of cooling events for cases where CBO is not isolated (References B1.2, B1.3 and B1.7). Reference B1.2 evaluated the seal conditions for an N-9000 loss of seal cooling event. The test included a prototypical installation. The facility was heated to an inlet temperature of 540°F. The CBO temperature (representative of the vapor seal cavity) remained below 300°F (See Figure B1.3-1). BJ/SU tests performed for both a static and dynamic loss of seal coolant events indicate that when the RCS simulated temperature is in the range of 516 to 530°F the temperature of the vapor seal cavity was between 400 and 420°F (see attached Figures B1.2-1, B1.2-2 and B1.2-3.)

5. *The discussion in Section 5.3.2 (pp. 5-11 & 5-12 ¶ 1) that the vapor seal will not pop-open, blowing down to atmospheric pressure.*

RAI 1.3.5 Response: When the fluid in the upstream cavity has less than 50°F subcooling and the pressure drop across the seal is greater than one half of the absolute pressure, there exists a potential for the seal to pop-open. These conditions can exist at various seal stages when the CBO is not isolated. Prototypical tests performed on a BJ/SU pump seal demonstrated that the seal stage is capable of maintaining seal integrity for a range of system temperature between 250 and 420°F and system pressures from 150 to 700 psia. Subcooling during this test varied from 30 to 150°F (See RAI 1.2). Similarly, N-9000 prototype tests indicated that with CBO isolated, vapor seals will not pop-open for pressures up to 2400 psia (subcooling during this test was as low as 55°F). Leakage through the seal during these tests was noted to increase, however, in all cases, the actual leakage vapor was not significant (See Table 1).

Table 1

a,c

Test	Description	Vapor Seal Condition	Leakage (gpm)

A review of actual plant LOSC events does indicate that vapor seals have the potential for a small amount of leakage, but at no time was a catastrophic failure of a vapor seal recorded (See responses to RAIs 1.7 and 1.8).

6. *The indications that sufficient subcooling is achievable for all potential accident conditions, although essentially none of the plants' procedures require at least 50°F subcooling for all these conditions.*

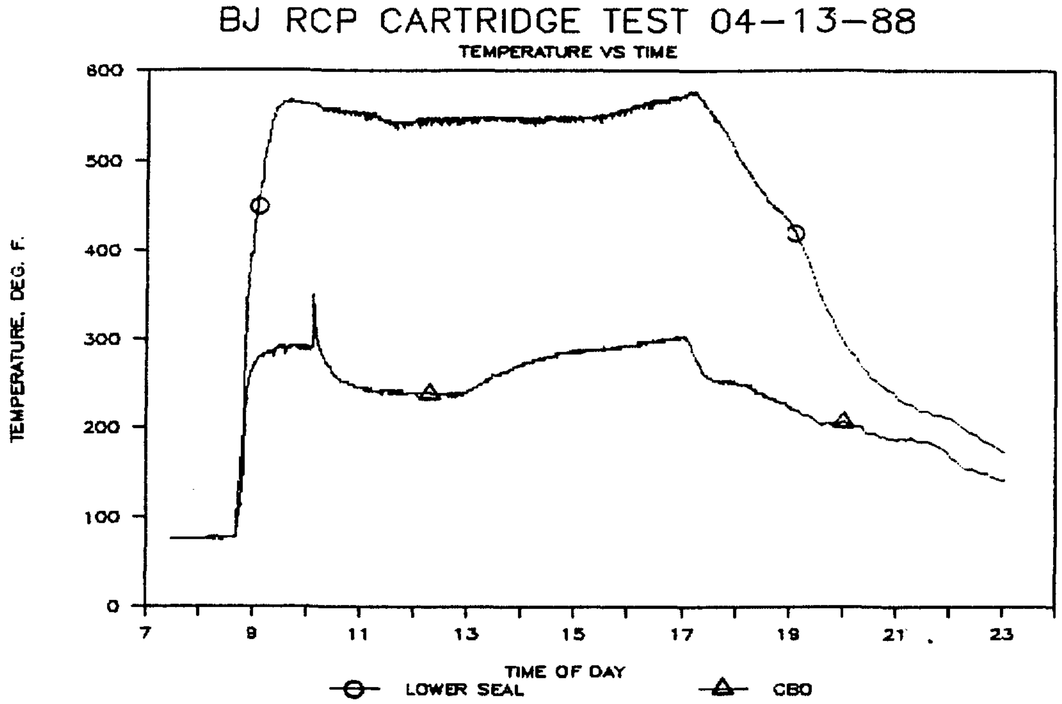
RAI 1.3.6 Response: For SBO conditions, operators will have a limited amount of equipment available for controlling RCS subcooling. However, 50°F subcooling in the cold leg will be maintained for a period of 3 to 4 hours without operator intervention (See response to RAI 1.2). For non-SBO loss of seal cooling events, operators will have adequate resources available to cool down the plant while controlling RCS subcooling. The 20°F subcooling requirement contained in EOPs is intended to avoid cavitation of the RCP. Plant responses suggest that the plant operators will maintain a comfortable 50°F margin to the required subcooling.

7. *The conclusion that the current generation of RCP seals for the BJ and Sulzer (BJ/SU) RCP designs are not expected to be significantly impacted by binding failure (pg. 4-3 ¶ 5). Note that the preceding text and some of the data points in Figure 3.4-1 (pg. 3-12) seem to refute this assertion. In this section, the cited test indicates a stage failure occurred for a BJ/SU seal exposed to 400°F for more than 70 hours and the cited incident at MP2 indicates a LOCCW event resulted in a stage failure for a BJ/SU seal exposed to 530°F for about four hours. Given that the exposure temperatures for a RCP stage may exceed those of the cited test and incident, it is not clear how the conclusion that binding failure is not expected to occur is supported.*

RAI 1.3.7 Response: Nitrile is a low temperature elastomer with a maximum recommended operating temperature of 250°F. Tests of this material performed by Rhodes et. al. indicated that the U-cups will embrittle to a glass-hard state after 8 hours of high temperature exposure. The advanced seal designs have eliminated the use of Nitrile U-cup follower in favor of an ethylene-propylene ring design which has better temperature endurance. Testing of ethylene-propylene O-rings indicated some extrusion, small changes in hardness and no leakage. Similar conclusions were obtained for prototypical O-rings tested at Kalsi Engineering Laboratories. No operational events have indicated ethylene-propylene elastomer failure as a cause of a BJ or Bingham RCP seal failure.

Following the BJ/SU test, post-test inspections were consistent with the above observation. The inspection indicated hard, brittle U-cups. Flexibility of the O-rings had been retained but the O-rings had taken a compression set. (Reference B1.3, Section B).

Figure B1.3-1
Plot of Lower Seal and CBO Temperature vs. Time



RAI 1.4

The topical report provides the general model for seal performance, but this model will involve a number of plant-specific considerations. To ensure a consistent implementation of the model, the topical report should identify and provide guidance on how to treat the plant-specific considerations. For example:

1. *Some plants do not isolate CBO for LOCCW and/or station blackout (SBO) events. Please describe how these plant-specific operating conditions impact and should be reflected within the model.*

RAI 1.4.1 Response: Plant-specific procedures would be considered by the individual utilities upon model implementation. If CBO is not isolated, the tables that utilize "CBO not isolated" data should be used. If CBO is isolated within 20 minutes, the associated "CBO Isolated" tables should be used and if CBO is isolated sufficiently early to avert significant heatup (within 10 minutes), the associated "CBO Isolated within 10 minutes" tables should be used. Given that the RCPs need to be tripped before isolating the CBO, the tables associated with "CBO Isolated within 10 minutes" would only be used with SBO sequences because the RCPs will automatically be tripped as a result of the initiator.

2. *Section 5.2 (pg. 5-4 ¶ 2) states that about 35,000 gallons of RCS inventory must be lost before incipient core uncovery in the smallest CE plant. As such, for the two-stage failure condition for the System 80 design at the sustained uncompensated leakage rate and the three lower-stage failure condition for the other plants, the identified inventory loss could occur well within the typical 24-hour mission time. If core uncovery could occur within the mission time for failures of less than catastrophic failure of all stages, then these additional accident scenarios would need to be addressed by the plant-specific implementation of the model. This may require that a two-stage failure condition be addressed, at least for a SBO accident scenario in which power is not recovered within the time frame required to avoid core damage. These scenarios do not support the conclusion of this paragraph that the seal is considered functional unless all seal stages have failed. Please describe under what conditions the model is not applicable (e.g., sustained SBO for greater than a specified time period) or how these conditions are to be addressed and/or confirmed in the plant-specific application.*

RAI 1.4.2 Response: This issue is plant specific. RCS inventory is proportional to plant power level. Core uncovery typically requires that approximately 70% of the RCS inventory be lost. For PVNGS, core uncovery would require the loss of greater than 70,000 gallons of inventory. A seal LOCA for PVNGS will spill RCS liquid at a rate of only 17 gpm per pump when the RCS is at full system pressure. Thus, for a single RCP seal failure, core uncovery would not occur in less than 24 hours. This remains true even if 4 RCP seals fail since the faster depressurization will reduce the break flows. The extended time to core uncovery is a feature of the KSB RCP thermal barrier design. All CE PWRs other than Palo Verde utilize BJ pump designs. CEFLASH-4AS was used to estimate the time to core uncovery following an RCP seal leak with rates consistent with the maximum leakage flow through an RCP thermal barrier (see Table 5.2-3 of CE NPSD-1199P, Rev 0.). Results are shown below.

Time to Core Uncovery Following Onset of RCP Seal Leak			
Plant Category	RCP Seal Leakage (Full Pressure)-gpm	1 RCP Seal Leak (Hrs)	4 RCP Seal Leaks (Hrs)

a, c

The model does not integrate the impact of this incremental time in the assessment of core damage. The incremental times identified above may be included in plant specific analyses.

3. *The RCP seal performance during a LOSC event is dependent on operator actions that are plant-specific and non-uniform as indicated in the topical report. Section 5.3.2 (pg. 5-7 .3.2 ¶ 2) notes that, for LOCCW events, it may take 10 minutes for the operator to diagnose the event and trip the RCPs. However, other sections (pg. 6-2) describe the desire to perform other actions within this initial 10-minute time window (e.g., isolating the CBO path) that would tend to occur after the RCP trip action. It is not clear how the operator action to isolate the CBO path could possibly be performed within 10 minutes if it takes that long just to diagnose the event and to trip the RCPs. How are these plant-specific and inter-related operator actions determined to be achievable for all the LOSC accident conditions, and how are the ensuing human error probabilities to be reflected in the model? Please provide a discussion of how the proposed model for RCP seal failure includes the plant-specific operator actions, and please describe the resolution of the apparent inconsistencies regarding operator actions.*

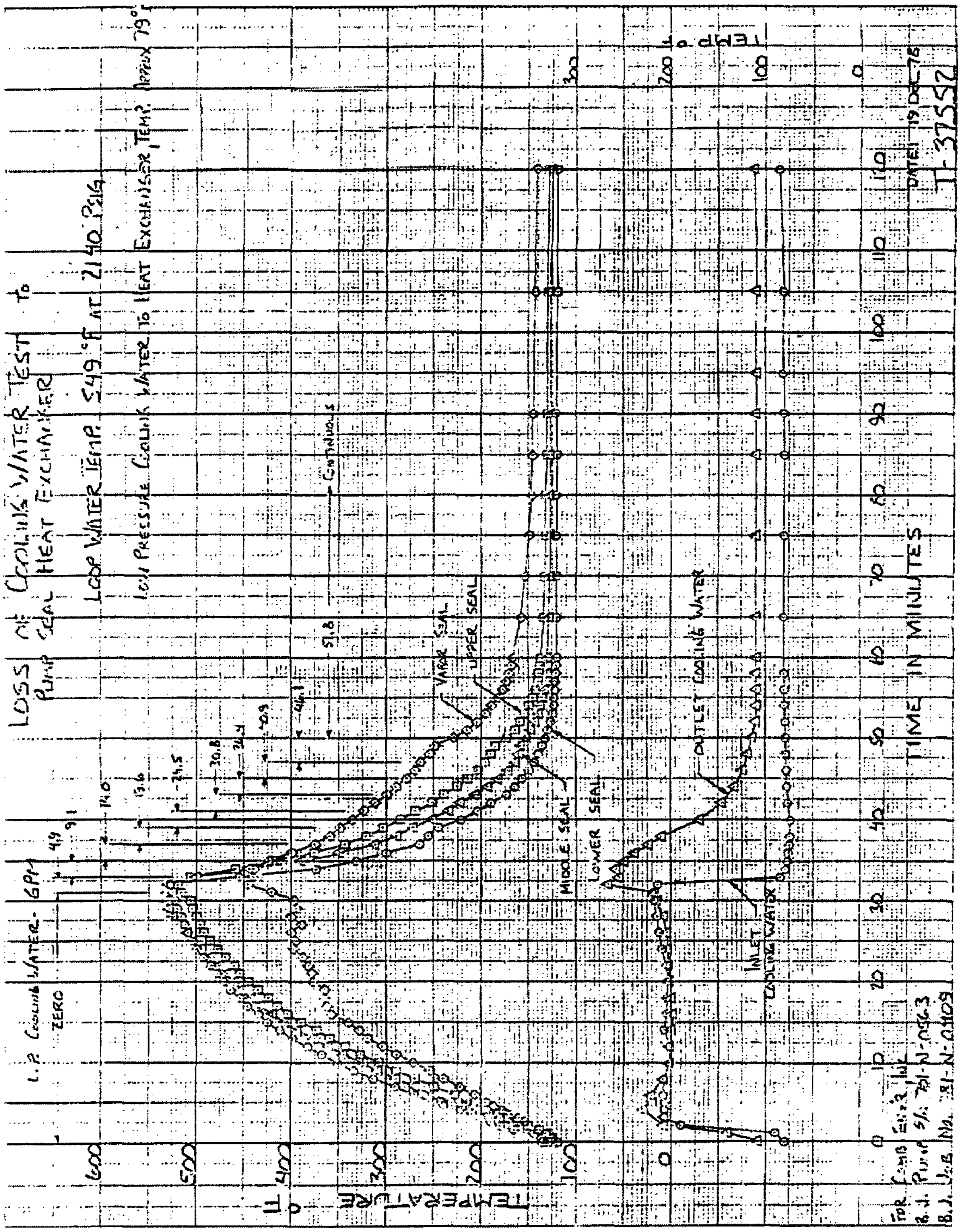
RAI 1.4.3 Response: The plant accrues two benefits from isolating CBO. First, early isolation of CBO (within the first 10 minutes of loss of seal cooling) would maintain the RCP seal stages well below the RCS temperature and hence minimize the potential for stage pop-open. Loss of component cooling water test performed by BJ for San Onofre on an operating RCP indicated that fifteen minutes into the loss of seal cooling event the lower, middle and upper seal stages had only achieved a temperature of between 400°F and 425°F. The vapor stage temperature would be closer to 350°F (see Figure B1.4-1). Isolation at this time would ensure a high level of seal subcooling during the loss of seal cooling event.

Second, CBO isolation de-stages the seals. That is, it removes the pressure drop across the lower three seal stages and applies the total system pressure drop to the last (or vapor stage). For four stage seal plants, this results in a large pressure drop at the lowest temperature seal. Pop-open of the lower stages would be averted due to the high seal back-pressure (lack of pressure drop); the vapor stage would be subcooled relative to the RCS pressure and would not pop-open. N-9000 tests investigated seal operation during CBO isolated conditions. No pop-open or bistable leakage was observed for a fully pressurized upper seal subjected to a more than 2200 psid pressure drop and an upstream fluid temperature of 500°F.

4. *The topical report contains a parenthetical statement (pg. 5-8 ¶ 3) that the previously stated guidance on not restoring CCW if it has been lost for more than 10 to 30 minutes was based on BJ/SU seal designs and that it is preferable to restore CCW for the CE units with N-9000 seals. What is the impact of implementing or not implementing this guidance at the CE plants with N-9000 seals, and how is this impact reflected in the model?*

RAI 1.4.4 Response: Restoration of cooling to the seal is desirable following a LOSC event. Depending on the temperature reached during the event, disassembly and inspection may be warranted before returning the equipment to service. Sulzer recommends that the seal be disassembled and inspected if it was exposed to temperatures higher than 260°F irrespective of time at temperature.

Figure B1.4-1


LOSS OF COOLING WATER TEST TO PUMP SEAL HEAT EXCHANGER
LOOP WATER TEMP. 549°F AT 2140 PSIG
TIME IN MINUTES
TEMPERATURE °F
UPPER SEAL
MIDDLE SEAL
LOWER SEAL
OUTLET COOLING WATER
INLET COOLING WATER

RAI 1.5

Even if a RCP seal stage does not pop-open (i.e., it is hydrodynamically stable), it may leak substantially (e.g., greater than 200 gpm) (See NUREG/CR-4821, p. iv.). In fact, with the Westinghouse RCP seals, the 182 gpm leak when the second stage seal pops open is caused by the increased leak rate of the first stage seal, although the first stage seal remains hydrodynamically stable. The first stage seal face separation becomes relatively large, but the axially moveable first stage seal face does not move to the limits of its travel, and the relatively large seal face separation is stable with respect to small changes in fluid conditions. If the first stage had also popped open, the leak rate would be even greater, about 480 gpm per pump. The topical report does not consider this possibility.

An example of the relevance of this possibility may be seen by referring to Table 5.3-6 (pg. 5-12). If the third-stage seal fails, and if the second-stage seal inlet conditions are less than 50°F subcooled, the second stage may pop-open. Then, in order to have a large leak, it is not necessary for the first stage seal to pop-open; it is only necessary for conditions to be such that the leakage through the first seal stage be large. The fact that the back-pressure on the first seal stage is low (after the second stage seal pops open) makes this more likely. Finally, the fourth-stage seal may fail after the other three fail, because of the low back-pressure. The failure could be a pop-open failure mode, or it could be a case where the seal faces have a large separation, although the seal remains hydrodynamically stable, as was discussed for the first-stage seal. This type of common cause failure (CCF) mechanism for developing a large leak from a RCP seal package does not appear to be included in the model.

Another example is that, even if the CBO line is isolated early, failure of the vapor seal may result in large leakages. If the vapor seal fails, staging of the pressure across the lower three seal stages, increased flow through these seal stages, and increased heatup of the seal stages will all occur. This condition would have the potential for multiple stages of the pump popping open, and large amounts of leakage through the first seal stage could occur even if it remains hydrodynamically stable. It does not appear that this type of CCF is included in the quantification of the RCP seal failure model presented in Chapter 9 of the topical report.

Please address the above identified considerations and conditions.

RAI 1.5 Response

The postulated scenarios have not been observed in practice nor are they likely. The BJ type seals have not indicated significant bistable behavior. Each seal stage in the seal package is designed to withstand full system pressure. The closest example of bistable behavior may be inferred from the upper and vapor seal behaviors in the BJ/SU designs from Reference B1.3. In this instance, seal leakage through the vapor seal was less than 0.27 gpm. Based on that test data the BJ/SU vapor seal stage was able to take a 600 psid pressure drop for more than one day while exposed to 400°F fluid without failure or pop-open. The BJ/SU upper stage seal exhibited some transient behavior where it may have operated in a bistable region. In the 37 to 45 hour portion of this test, the pressure drop across the upper stage reduced to about 150 psid. Since CBO was operating, the flow through the pressure breakdown coils at that time would be 1.0 gpm x (150 psid/750 psid)$^{1/2}$ or 0.45 gpm. Thus, the bistable seal leakage condition would be about 0.55 gpm. At this time, the local subcooling for the upper stage was about 15°F. In another instance, between 45 hours and 55 hours a 500 psid pressure drop was imposed on the upper seal at temperatures of 500°F (~44°F subcooling) so that the flow through the pressure breakdown device would be reduced to accommodate a seal leakage flowrate of about 0.2 gpm. Test temperature and pressure traces are presented in the attached Figures B1.2-1 through B1.2-3.

Even though the upper seal indicated some transient behavior, no direct coupling was noted between the upper seal stage behaviors and the upstream seal stages. Both the middle and lower stage pressure remained relatively unchanged.

The N-9000 test (Reference B1.2) included conditions where the CBO was operating and when CBO was isolated. The CBO isolated cases indicated the vapor seal held a greater than 2200 psig pressure drop without failure for 8 hours following a loss of seal cooling. Liquid subcooling upstream of the last seal stage was typically greater than 55°F (leakage past the seal face was maintained at 0.04 gpm throughout the test).

Sixteen loss of seal cooling events have occurred at CE-designed PWRs using BJ/SU, N-9000 or Sulzer seals (see revised table 9.2-12 and responses to RAIs 1.7 and 1.8). Several of these events have resulted in seal conditions that resulted in two-phase flashing across the faces. Pop-open appeared to exist for several tests and was generally limited to stage 3 of the 4 stage seal. In several instances a coupling between stage 2 and stage 3 seals was inferred, however, stage 2 seal failure was not identified. As observed in the experiments, seal stage 4 (vapor stage) remained stable regardless the condition of the upstream seals. Furthermore, of the 38 potential affected stages for pop-open, only six pop-open events were noted within 2 hours of the onset of the loss of cooling event. (Section 9 of CE NPSD-1199-P has been revised extensively in response to these RAIs. Table 9.2-12 of the revision summarizes the event data used to quantify the probability of pop-open failures.)

The question postulated that failure of the vapor stage would begin a cascading "unzipping" of the four seal stages. This scenario is modeled but has an extremely low probability of occurrence. Operation of the vapor stage under adverse conditions during test and events has not resulted in a single failure of the vapor seal to maintain pressure. Certain events have resulted in small (~ 1 gpm) increases in seal leakage. Lower seal stages exposed to harsh conditions do not indicate a pop-open event even when the inlet seal temperatures are near saturation conditions. Independent of the downstream conditions, the seal will perform satisfactorily against full RCS pressure (as would any of the four stages), as long as the lowermost seal entry fluid is subcooled by 50°F.

In summary, experimental evidence and operating experience suggests that the cascading nature of the seal failure postulated in the RAI is inconsistent with the observed behaviors of the seal.

1. While coupling is likely between seal stages 2 and 3 due to the low pressure high temperature conditions which results in low subcooling, stage 3 failures have not been associated with equivalent stage 2 pop-open failures.

2. Tests demonstrate that a single stage can withstand full system pressure while operating at elevated temperature. Other tests confirm that even when operating near saturation conditions, seal leakage would be low (less than 1 gpm).

3. While there is an impact in back-pressure on the upstream stage, the stages are intended to perform their function under full system pressure. Thus, the first stage was assumed to be subject to pop-open only when the RCS subcooling is less than 50°F.

4. The last stage operates with atmospheric back-pressure. In no cases did the vapor stage exhibit pop-open, whether or not the CBO was operating. Vapor stage operation under high RCS pressure (CBO isolated) will be subcooled and therefore not subject to pop-open. For

CBO operational conditions, the driving pressure in the vapor stage would be much lower. Based on experiments, leakage past the vapor stage would be small.

A review of the issue did uncover one coupling mechanism that was not previously considered. That is, should the vapor seal fail or leak excessively for any reason while CBO is isolated, the failure would re-stage the seal and the lower stages would become subject to pop-open failures as well as thermal effects. Thus, the failure rates for the subsequent stages would be based on CBO operating conditions, not CBO isolated conditions. This feature has been integrated into the model by assuming that all sequences in which the vapor seal fails, the upstream seals would be treated as if CBO were not isolated. The fault tree models in Figures 6.2-1 and 6.2-2 of CE NPSD-1199-P have been revised to include this new coupling mechanism for the CBO Isolated conditions and to include a new failure scenario involving failure of the excess flow check valves and failure of the lower stages for the CBO Not Isolated conditions. The revised fault trees are presented in Figures 6.2-1 through 6.2-4.

RAI 1.6

The topical report does not address the expected leakage rates for a number of RCP seal stage or related component failure modes. The report should provide these leakage rates. It should also describe how these leakage rates are bounded and/or reflected in the model, including:

1. *The blowout of various O-rings and secondary seals (i.e., complete loss of these type seals).*
2. *The pop-open of a single or multiple seal stages, including the vapor seal with the CBO line isolated.*
3. *The various RCP seal stage failure modes with the CBO line not isolated.*
4. *The failure of the excess flow check valve(s) to limit flow.*

RAI 1.6 Response

The topical report does not address O-ring failures as these failures would not result in significant changes in seal leakage. Precise calculations are therefore unnecessary. The existing tables (Tables 5.2-1 and 5.2-2) that estimate the impact of individual and multiple seal stage bypass bounds the impact of these elastomer failures. Incomplete seal failures will only marginally decrease the flow resistance between the two adjacent cavities. (As presented in RAI 1.5, even a seal failure that reduces the seal stage pressure drop from 750 psid to 150 psid will pass only 0.55 gpm.) Thus, the impact would be less than the situation if the seal had catastrophically failed.

Complete loss of all seal elastomers has not been studied. However, the hypothetical loss of all seals would likely render the seal incapable of performing its function, as flow would likely leak around all seal stages. This degree of failure is considered incredible. Conceptually, the elastomer failure probability considers failures associated with extrusion and binding and general elastomer failure. Thus, this probability, however unlikely, is considered.

The following paragraphs will specifically address some nuances associated with the four points identified.

1. *The blowout of various O-rings and secondary seals (i.e., complete loss of these type seals).*

   As discussed above, these failures are bounded by complete stage failure assessments included in Table 5.2-1 and 5.2-2 of the report.

2. *The pop-open of a single or multiple seal stages, including the vapor seal with the CBO line isolated.*

   Pop-open failure leakage rates based on single and multiple seal stage failures are included in Table 5.2-1 and 5.2-2. Pop-open is assumed to result in a hydraulic bypass path. Note that seal stages are in series. There is no fluid pathway out of the seal without passing through at least three stages of a four stage seal. If CBO is isolated, seal leakage requires the failure of the vapor seal.

3. *The various RCP seal stage failure modes with the CBO line not isolated.*

   Leakage could leave the seal via the CBO line if CBO is not isolated. The excess flow check valves limit this flow path. Leakage will occur if all of the seal lower stages fail and the excess flow check valve fails to stop seal flow. This leakage could be significant; the amount will depend on plant responses to the event (e.g. RCS depressurization). This failure mode has been added to the seal failure model. The fault tree models in Figures 6.2-1 and 6.2-2 of CE NPSD-1199-P have been revised to include a new coupling mechanism for the CBO Isolated conditions, this new failure scenario involving failure of the excess flow check valves, and failure of the lower stages for the CBO Not Isolated conditions. The revised fault trees are presented in Figures 6.2-1 through 6.2-4.

   Note that failure of fewer than all of the first three stages plus the vapor stage will not result in significant RCS leakage.

4. *The failure of the excess flow check valve(s) to limit flow.*

   Failure of the excess flow check valve to limit flow was not considered. The most likely failure mode for this type of valve is to fail closed. However, should the valve fail to close RCS leakage following failure of all the lower seal stages would be significant. As noted above, this failure mode has been included in the model update.

RAI 1.7

Some of the operational plant data and RCP seal test data used in the topical report (Table 8-1, pp. 8-2 - 8-6) to quantify the proposed seal failure model has been questioned in the past regarding its accuracy and the actual conditions occurring at the time of the LOSC event (e.g., C. Ruger letter to S. Khalid Shaukat, USNRC, dated June 24, 1994, on the subject of CE Owners Group (CEOG) LOSC events and tests). The Ruger letter states that it appears that many of the LOSC challenges to the seals are not valid challenges that would result in the likelihood of seal failure as determined by generic issue GI-23 research. In addition, note that all of the LOSC challenges were only for BJ/SU or Klein, Schanzlin & Becker (KSB) RCP seal designs. (The Waterford events were listed only as BJ, but could possibly have been for the N-9000 design.) The BJ/SU design is now only used in one plant, and the KSB design is not in any plants. These are very important points because the data is being used to obtain estimates of the seal stage failure probability.

As an example of questionable data, Ruger noted that the St. Lucie Unit 2 event of 12/19/84 is not very clearly described. The description states that seals on pumps 2B1 and 2B2 failed, but then it states that no stage failure was observed. Also, in Table 9.2-4 (pg. 9-14), the event is listed as *not applicable. If the pumps were stopped during the event, and if a seal stage failed, it would seem to be applicable. Even if, in an operating event, CCW was lost to the RCP seals, the situation is not the same as a SBO or total LOCCW. The situation is not the same because the charging pumps were likely available and the RCS pressure and the subcooling margin could be better controlled than in a SBO or LOCCW, which would affect the charging pumps.*

Please address the deficiencies raised in the June 24, 1994 letter from C. Ruger. Please also clarify the entries in Table 8-1 (pp. 8-2 - 8-6) and related Chapter 9 tables (pp. 9-5, 9-9, and 9-14) to address the numerous event description inconsistencies and failure modeling impacts, including:

1. *Event ANO2-1 is listed as a SBO, but it was only a partial loss of AC power. Also, its short duration of 6 minutes would make it not applicable for most potentially significant failure modes. Even so, it had an increase in vapor seal leakage, though prior text indicates it should not be susceptible for such a short duration event. This leakage through the vapor seal for such a short duration event should be explained.*

RAI 1.7.1 Response: Due to the short duration of this event, it was not included in the success or failure counts used to quantify the model. There is no additional information available for this event. Plant staff does not recollect any particular problems with the seal after the event or any prolonged leakage. This event was of such a short duration that the vapor seal would not have seen any adverse conditions associated with a loss of cooling.

2. *ANO2-2 was not a LOCCW, but a degraded CCW flow. The applicability of this event is questionable because some CCW flow may have existed.*

RAI 1.7.2 Response: No additional information on this event was available from the plant. Given that the event descriptions indicated only "degraded" CCW flow without specifying how much or how little CCW flow was available, Westinghouse concurs that this event might not have involved a total loss of CCW flow and this event has been deleted from Tables 8-1, 9.1-1, 9.2-1 and 9.2-4 in CE NPSD-1199-P. The revised tables are included in the revision of Section 9 of CE NPSD-1199P. Note that due to other changes, the former Table 9.2-4 has been renumbered as Table 9.2-12. (Note that this question implies that any CCW flow to the seal is sufficient to preclude seal failure.)

3. *FCS-2 indicates one failed stage on one pump, but the seals on all pumps were replaced. What were their conditions? Were they degraded or leaking substantially, but not failed?*

RAI 1.7.3 Response: During this event, there were no indications of seal stage failures. However, the seals exceeded the manufacturers recommended operating conditions. Therefore, as a precautionary measure, Fort Calhoun replaced all seals in accordance with the manufacturer's recommendations.

4. *FCS-5 is a short-duration exposure during startup. Were the conditions applicable to full-power operations?*

RAI 1.7.4 Response: Events with duration of 0.1 hours or less were not used to quantify the model. They were included in the lists for reference only. To avoid confusion, the calculation for the interval 0 to 0.1 hours has been removed from Tables 9.2-1 and 9.2-4. The revised tables are included in the revision of Section 9.

5. *FCS-6 is listed as the same event as FCS-5, but it is listed separately and counted separately in Table 9.2-1 (pg. 9-9). This double-counting appears to artificially and inappropriately lower the failure probability*

RAI 1.7.5 Response: The original information used in CE NPSD-755 indicated that two similar events had occurred in July 1992. Fort Calhoun has the available operating information and can find only the event on July 1. Therefore, FCS-6 has been deleted from Tables 8-1, 9.2-1 and 9.2-4. The revised tables are included in the revision of Section 9.

6. *MNS2-1 indicates that lower seal temperature increased (275-330°F), but this is not at the exposure temperature level expected to cause some of the failures for which it is counted in Chapter 9.*

RAI 1.7.6 Response: For Event MNS2-1, the event data indicates that the temperature in the lower seal stage was beyond the strip-chart range of 355°F for 3 hours and 45 minutes. Since the plant was in hot standby with an RCS temperature of about 530°F and CBO was operating, it is expected that the temperature in the lower stage would be about the same.

7. *MNS2-2 occurred while the plant was in hot standby. Were the conditions applicable to full power operations?*

RAI 1.7.7 Response: At the time that event MNS2-2 occurred, Millstone 2 was in hot standby with the RCS temperature at 530°F with the system at about 2200 psia. The stage failure on this seal manifested itself on RCP restart shortly after cooling was restored.

8. *PV2-1 and PV2-2 occurred before commercial operations. Were these conditions applicable to full power operations? Further, PV2-2 appears to be related to PV2-1 in that the earlier event is what led to the degraded seals and the latter leakage events. Therefore, it appears that these events should not be treated as separate events.*

RAI 1.7.8 Response: At the time that event PV2-1 occurred, Palo Verde Unit 2 was in hot standby with the RCS pressure and temperature at normal operating values. Hot standby conditions are covered by Technical Specifications and are the same for both commercial and pre-commercial operation. Event PV2-2 describes a stage failure that occurred during power operation about 3 months after event PV2-1. It is believed that this stage failure is related to the effects of the conditions experienced during event PV2-1 and was originally included in Table 8-1 for completeness. This event has been deleted to avoid confusion since it was not used for failure or success counts. (See revised Table 8-1) Note that the PVNGS data in general was only used for quantification of elastomer survivability as the PVNGS units had KSB seals. The elastomers used in the KSB seals are equivalent to the elastomers used in the other seal designs used by CE NSSS plants.

9. *PV3-1 illustrates an event - addition of hot RCS water without inter-stage cooling - that is not addressed by the model. Further, the temperatures are below 500°F. Thus, there is a question about the applicability of this event to specific failure phenomena. A stage failed, but it is not clear how it was counted.*

RAI 1.7.9 Response: The mechanism that lead to the failure described in event PV3-1 was unique to the KSB seal design and could not occur on the Byron-Jackson SU seals, the Flowserve

N-9000 seals, or the Sulzer Balanced Stator seals. This event was used for evaluating the ethylene-propylene elastomer failure potential because the elastomers are equivalent but it was not used for evaluating the potential for pop-open failure. Palo Verde was the only plant to use KSB seals; these were replaced with Sulzer Balanced Stator three stage seals in 1996.

10. *The report states that SL2-T shows that seals can withstand extended SBO events, but it also shows cracking, deformation, and hardening that would suggest potential for failure. What temperatures were reached in the test? Are these applicable to full-power operational events?*

RAI 1.7.10 Response: The test lasted 70 hours. Nitrile U-cups were severely degraded and some O-ring deformation was noted. No stage failures resulted. The test was conducted at ~520°F with seal temperature/pressure exposure typical of post-accident CBO operation. Note that RCS cooling during an actual event would reduce RCS temperature and pressure exposure and further mitigate the seal failure threat.

11. *The report states that no stage failures were observed for SL2-2, but it also states that two seals failed. The Nuclear Plant Reliability Data System (NPRDS) indicates that one RCP seal was leaking excessively and suffered significant seal damage. How was this discrepancy resolved and why is it appropriate to consider this as "no failures" in Chapter 9?*

RAI 1.7.11 Response: There is limited additional information available for this event. Discussions with the plant personnel indicated that their typical practice was to call a stage failed if the pressure breakdown across the stage was < 100 psi and if the operating environment exceeded the conditions recommended by the manufacturer for more than 10 minutes, especially if there was any increase in leakage above the nominal limit. Plant personnel advise that catastrophic seal failure did not occur. However, based on similar information for other events, it is possible that the third stage on the two affected RCPs "popped-open." Therefore, two additional stage failures have been included in the revised Tables 8-1, 9.1-1 and 9.2-4.

12. *SL2-3 indicates that the third stage was degraded and possibly failed on two RCPs, but this is not reflected in Table 9.1-1 (pg. 9-5). How were these potential failures addressed?*

RAI 1.7.12 Response: As indicated in Table 8-1, it appears that the third stage on two of the pumps might have failed. These two stage failures were treated as pop-open type failures as shown in the revised Table 9.1-1 and 9.2-4 for event SL2-3A.

13. *SOS2-T indicates cracked vapor seal rotating ring and deterioration of elastomers. How were these potential failure precursors factored into the data of Chapter 9?*

RAI 1.7.13 Response: The pump was operating with a loss of CCW (i. e., without seal cooling). All seal stages maintained their sealing capability during the test and throughout the following cooldown. This test demonstrated the ability of seals to remain intact following a delayed RCP shutdown. Similar demonstrations of this capability have been performed on BJ seals and have occurred in the field. This information was used to estimate that, while damage may occur to the seal, it will serve its safety function for a minimum of ~1 hour. Field experience has resulted in more than 30 minutes of operation without cooling with limited damage. It was extrapolated that seals would maintain their integrity following operation without cooling for periods of up to 1 hour. This has been revised downward to 20 minutes to stay within the data and to simplify the modeling with respect to CBO Isolation timing as shown in the revisions to Section 6.

14. *Item 4 in Section 9.1.1 (Pg. 9-4) states that events of UNKNOWN duration were attributed to the "less than one-hour exposure" class. However, if these events were under 10 minutes, it could be argued that they should not even be counted as a challenge. If these events resulted in a degraded or failed stage that is counted in the data, then it is probably appropriate to place them in the "less than one-hour" class. However, if no failures are indicated, they should not be included at all. Please adjust the data accordingly or provide a justification for including extremely short-duration events that probably were not of sufficient duration to challenge the RCP seal stages.*

RAI 1.7.14 Response: All of the events with duration of less than 0.1 hour were included in the report for reference. These events were not used to determine success counts or failure counts.

15. *WSES3-1B shows that for pop-open it is not the duration of the event that is important, but the time to the proper conditions, which occurred at 40 minutes. For this event, Table 9.1-1 (pg. 9-5) attributes 6 stages to one RCP. Please correct the number of stages exposed in the table.*

RAI 1.7.15 Response: Table 9.1-1 has been corrected.

16. *The stage elastomer failure probabilities were established using the experience data by observing the number of stages exposed to a high-temperature environment, which is parenthetically identified as 500°F (pg. 9-7 ¶ 3). Most of the experience either does not identify the temperature of the individual stages or indicates that they were less than 500°F. However, Table 9.2-1 uses many of these events to determine the above failure mode probability, even though these events may not have reached this temperature. Please explain how the events used to establish the failure probabilities were determined to have reached a high temperature.*

RAI 1.7.16 Response: Temperatures were from the plant conditions and results of loss of seal cooling tests on similar seals. For example, seal tests indicated that after ~ 0.5 hour, the three lower seal stages reached an equilibrium condition of slightly below the inlet/test stand temperature. The vapor stage is seen to be at a considerably lower temperature. It was assumed that for loss of seal cooling events with CBO operating and RCS temperatures at hot standby or at power, seal stage temperatures in the vicinity of seal stages 2 and 3 would be slightly lower than the RCS temperature and the temperature in the lower seal stage would be close to RCS temperature. The vapor stage seal would see a much lower temperature due to the presence of saturation conditions and heat losses to the ambient.

17. *The number of failures identified in Table 9.2-4 (pg. 9-14) may be incorrectly calculated in that they do not recognize previous stage failures. The failure count may need to be cumulative, depending on how the model uses the information. Thus, failures that occurred in the first hour may need to also be counted as failures through the second hour and beyond because these stages did not make it through the interval in question. In other words, it is a given that these stages have already failed and will not survive the next interval. This will result in an increase in calculated failure probabilities. This also impacts Tables 9.2-5a through 9.2-5f (pp. 9-16 and 9-17).*

RAI 1.7.17 Response: All pop-open failures will be taken to occur in the 0.5 to 1 hour time interval. This is consistent with the onset of limiting thermal hydraulic conditions as indicated by loss of seal cooling experiments. Elastomer failures were associated with Nitrile U-cup deterioration. Experimental data on EP elastomer installations indicates excellent performance through 8 hours. Only one seal stage failure was noted to be caused by Nitrile elastomer degradation. The event involved isolation of CCW to the seal for more than 4 hours while the plant was in hot standby with the pump shutdown. The failure was placed in the > 4 hour interval because the stage failure after seal cooling was restored and the pump restarted.

RAI 1.8

Please justify the applicability of the events identified in Chapter 8 to their use in deriving the failure probabilities in Chapter 9. Include a discussion of the validity of these operational and test data, specifically addressing:

Did a complete LOSC occur during full-power plant operations?

Were individual stages actually challenged, and did conditions for hydraulic instability, binding, etc. exist for each stage?

Did the tests actually model the potential stage conditions and challenges?

RAI 1.8 Response:

The response to RAI 1.7 provides additional information for a number of the events covered in Table 8-1. As a result of the re-evaluation of the events discussed in RAI 1.7, several of the events were removed from consideration. In addition, the event PV1-1 was also removed from consideration. Additional information provided by Arizona Public Service indicated that while both seal cooling and seal injection were lost during this event, there was a limited time period during which seal injection and seal cooling were unavailable at the same time. The remaining events represent occurrences in which seal cooling was lost during normal operation or the seal was subjected to plant conditions equivalent to normal power operation in terms of RCS temperatures and pressures. These events are summarized in the revised Table 8-1.

All the events considered are subject to prototypical system pressures and temperatures following a total loss of seal cooling. To ensure local seal conditions were sufficiently high to challenge the seal stage for elastomer integrity or pop-open, only events whose duration was at least 0.5 hour was considered. Tests show that by one-half hour into a loss of seal cooling event with CBO operational, seal stage temperatures in the lower three seals (for a four stage seal) would reach equilibrium temperatures (> 500°F) (See Reference B1.7). For events in which CBO is not isolated, subcooling for the third stage will be less than 50°F within about 0.5 hours; other seal stages will remain subcooled. Should the third stage pop-open, the subcooling in the second stage will be slightly less than 50°F subcooled. Therefore, events lasting ~ 0.5 hours or more are used for evaluating pop-open failure probabilities. For each such event, one challenge (for the third stage) is counted for each pump. If a pop-open occurs, one additional challenge is counted for the second stage that would then be less than 50°F subcooled. Thus, in the treatment of pop-open, the third stage was the only stage considered initially subjected to the phenomenon. If a third-stage pop-open occurred, the second stage was considered to be subject to pop-open conditions with the potential for a pop-open failure. Note that this logic is revised from that presented in the original report; where pop-open failure of stages 2 and 3 were treated simultaneously. The data review also indicated that most pop-open events may have occurred early and hence are not time dependent. This logic was also used when re-assessing the data.

All seal stages subjected to temperatures in excess of 500°F (typically three stages in a four stage seal) were considered in the calculation of elastomer integrity. Elastomer pressures varied from nominal 750 psid per stage to 2400 psid for selected stages.

All events involving a loss of seal cooling lasting less than 0.1 hour have been excluded because the seals would not be expected to experience elastomer failure or pop-open within such short exposure time. The temperatures in the lower three stages for a four stage seal (lower two stages for a three stage seal) would reach equilibrium temperatures within about 0.5 hours of loss of seal cooling given that CBO flow is not isolated. Therefore, only events involving a loss of seal cooling for 0.5 hours or more were used to evaluate the potential for elastomer failure. Tables 9.1-1, 9.2-1 and 9.2-4 of CE NPSD-1199-P have been revised to reflect these selection criteria.

RAI 1.9

The topical report presents a formula (pg. 9-7) for estimating the failure probability, Q, from data when zero failures were observed in a number of challenges, N, as:

$$Q=0.455/(2*N)$$

The origin of the expression is the median of a Bayesian posterior distribution for the probability, Q, when a non-informative prior of $1/\sqrt{Q}$ *is used, and a Poisson approximation to the binomial is used for the likelihood function. The numerator is the median value of the chi-square distribution with one degree of freedom. However, it would be more appropriate to use the mean value of the posterior distribution for Q. The posterior mean for zero failures is 1/(2*N), when the non-informative prior given above is used. The expressions for the posterior probability density function, the posterior mean, and the posterior median are given in NUREG/CR-2300, on p. 5-50. The quantity "T" in this reference is to be identified with "N," and the quantity "λ" in this reference is to be identified with "Q." If the mean probabilities are used instead of the median, the estimates are multiplied by a factor of 2.2 (i.e., 1/0.455).*

For the case of zero failures, the upper confidence limit on Q, for a confidence level α, is $Q_{upper} = -ln(1-\alpha)/N$. *By solving this equation for α, one finds that the Bayesian median value of Q corresponds to a confidence level of 20%. The Bayesian mean value of Q corresponds to a confidence level of 40%. The 50% confidence level of Q is -ln(0.5)/N, or 0.69/N=1.39/(2*N).*

All of the above presupposes a non-informative prior of $1/\sqrt{Q}$ *is used, which has not been justified. Since a probability is bounded by 0 and 1, a non-informative prior that is uniform between 0 and 1 could be used. With this prior, the posterior probability density function is proportional to the likelihood. For the case of zero failures, the (normalized) posterior density function for Q is N*exp(-NQ) and the Bayesian mean value of Q is 1/N, or 2/(2*N), which is an even higher estimate than the 50% upper confidence limit on Q. Summarizing these estimates:*

Estimate Type	*Point estimate of Q*
Bayesian Median (prior $1/\sqrt{Q}$)	*0.455/(2*N)*
Bayesian Mean (prior $1/\sqrt{Q}$)	*1.0/(2*N)*
50% upper confidence limit (prior $1/\sqrt{Q}$)	*1.39/(2*N)*
Bayesian Mean (flat prior)	*2.0/(2*N)*

Because point estimates of probabilities should be mean values, and not median values, the Bayesian median estimate should not be used. However, it is clear that the choice of prior has substantial influence on the results. If a flat prior is used, the Bayesian posterior mean is a factor of two greater than if a $1/\sqrt{Q}$ prior is used.

Please provide the justification for the formula used to calculate the failure probability, Q, from data when zero failures are observed in a number of challenges, N. Without an adequate justification for using the $1/\sqrt{Q}$ prior, the Bayesian mean with a flat (uniform) non-informative prior should be used (i.e., Q=1/N).

RAI 1.9 Response:

The $1/\sqrt{Q}$ prior is equivalent to the Jeffrey's non-informative prior. Use of the $1/\sqrt{Q}$ prior is consistent with the data analysis approaches presented in NUREG/CR-2300. Furthermore, as discussed by Atwood in EGG-RAAM-11041 (Reference B1.10), work performed by Box and Tiao (Reference B1.11) indicates that there are fundamental reasons for preferring the Jeffery's non-informative prior to the uniform prior. Westinghouse does concur that use of the Bayesian Mean would be more appropriate than use of the Bayesian Median. The text and calculations in Section 9 have been revised to reflect these changes.

RAI 1.10

The topical report states in Section 9.2.3 (pg. 9-11) that a pop-open seal stage failure requires the coincidence of three conditions: (1) elastomer binding, (2) movement of the RCP shaft due to depressurization of the RCS or differential thermal expansion of the RCP shaft, and (3) thermal-hydraulic conditions in the vicinity of the seal stage faces that are amenable to pop-open due to hydraulic instability. This statement is not in agreement with the results of the work done for generic issue GI-23. As noted in Section 2.2.1 of the BNL guidance document (G. Martinez-Guridi et al, "Guidance Document for Modeling of RCP Seal Failures," BNL Technical Report W6211-08/99, August 1999), <u>either</u> elastomer binding (in conjunction with RCP shaft movement) <u>or</u> thermal-hydraulic conditions leading to popping open is sufficient for RCP seal stage failure. An intermittent popping open mode does not occur if there is hydrodynamic instability. Unless cooling is restored, the seals remain "popped-open." Binding is a second way of having the seal faces separate, but it is not required for popping-open of the seal faces. Binding and hydrodynamic instability are two separate failure modes. Later in Section 9.2.3 (pg. 9-13), in the discussion of the pop-open mode of failure, the topical report states that, for short-duration events, there is insufficient time for the seal to be sufficiently deformed to prevent return of the stage to its seated position. But pop-open is just a question of hydrodynamic instability; it does not require deformation of the seal. NUREG/CR-4821 discusses the hydrodynamic instability mode of failure of a seal stage. Please correct these aspects of the topical report, including any *changes in the modeling and data to properly reflect the conditions and differences in the pop-open and binding failure modes, or explain how the conditions are appropriate for the RCP seals for CEOG plants.*

RAI 1.10 Response

Data obtained from tests on BJ designed seals and experiential data obtained from loss of seal cooling events indicates a low propensity of seal stages to pop open when subjected to low subcooling conditions and a similarly low potential for significant bistable operating behavior. Furthermore, stage failures subjected to subcooled inlet flow conditions showed a dependence on time. This transient behavior was noted in the third seal stage of BJ/SU seal SBO test (See attached Figure B1.2-3).

Based on that behavior, the likely scenario is that a small seal leak due to a minor pop-open could be exacerbated over time by degraded seal elastomers. This is also consistent with some seal stage failures. However, it was believed that such seal leakage would be associated with the BJ/SU Nitrile U-Cup seal design, which degrades at high temperature. No such behavior was noted in the N-9000 seal design. The only impact approach has on the analysis was in the binning of the pop-open failure data. The data has been reviewed and seal pop-open failures were re-binned to reflect the earlier potential onset of the "failure." Based on expected seal heatup, the stage local pressure and expected stage subcooling only the third stage was considered to be initially susceptible to pop-open for this binning. Thirty-eight (38) seal stages have been identified as having the potential for pop-open during loss of seal cooling events. This is based on events in which the seals were exposed to a LOSC event for at least 30 minutes and CBO was not isolated. For these events, 6 stage failures were classed as pop-open failures. The pop-open failure rate was computed as 6/38 or 0.16. Pop-open failures were not seen to propagate upstream. As previously discussed, a pop-open failure of stage 3 would result in a reduction of subcooling for stage 2. Therefore, the above data was used to estimate the conditional probability of stage 2 experiencing a pop-open failure given that stage 3 had popped open. There were 6 events in which a stage 3 pop-open failure appears to have occurred and no evidence of any stage 2 pop-open failures. Based on the response to RAI 1.8, the failure probability is estimated as: Q)0) = 1.0/(2*N) = 1.0/(2*6) = 0.08. However, the correlation between a pop-open failure of stage 3 and a pop-open failure of stage 2 is the fact that a stage 3 failure would expose stage 2 to pop-open conditions. Therefore, the same pop-open failure probability was used for both stage 3 and stage 2 for LOSC events where CBO was not isolated.

The present pop-open model is driven by local conditions. The only time dependence included is that associated with the delayed onset of first stage pop-open conditions (see RAI 1.2). Section 9 of CE NPSD-1199-P has been revised to reflect the revised treatment of pop-open failures.

RAI 1.11

The time dependence for the probability of the pop-open failure of the RCP seal stages (pg. 9-12 ¶ 2 and pg. 9-13 Figure 9.2-2) does not appear to be valid. If the seal stage is subject to pop-open, pop-open will occur as soon as the appropriate thermal-hydraulic conditions are present (i.e., it is a demand failure, not a time-dependent failure). Unless a probability-versus-time curve can be developed for these thermal-hydraulic conditions, there is no justification for assuming a time dependence for the pop-open failure mode. For the quantification of the event trees and fault trees, the pop-open mode of failure should be assumed to occur (if it occurs at all) as soon as the thermal-hydraulic conditions are favorable for its occurrence. Please either (1) provide the analysis that supports the time dependence of the development of the thermal-hydraulic *conditions that result in the pop-open failure mode, or (2) revise the resulting failure probabilities to reflect the fact that pop-open occurs (if it is going to occur) when the conditions are present and that it is not a time-dependent failure. Note that for the Rhodes model for Westinghouse RCPs, this time to the conditions for the second stage seal was assumed to be about 10 minutes.*

RAI 1.11 Response

The time dependence arose as a result of observations of BJ/SU experiments and events. As discussed in the response to RAI 1.2, experiments did not exhibit the pop-open phenomena. A re-assessment of the data suggests that seals were more likely subject to a bistable condition that would produce only minor leakage (0 to 3 gpm). No event indicated the total inability of a seal stage to hold pressure. There was some evidence (see for example stage 3 and vapor stage in BJ/SU hot standby test) that a seal allowed a small amount of leakage (0.2 to 0.5 gpm). These behaviors were observed to be quasi-steady; the seal failures were classified as pop-open failures based on this behavior.

RAI 1.12

The CCF of RCP seal stages in different pumps exposed to the same conditions is not explicitly addressed in the topical report. The statement in Section 6.3.1 (pg. 6-6 ¶ 3) that multiple RCP seals will be exposed to the same environmental conditions is a strong argument for CCF consideration, but this paragraph concludes that the model treats the RCPs independently. The condition of the seal faces may be important. If the seal faces in one pump are worn, it is likely that the seal faces in the other pumps will also be worn. Please modify the model to address this CCF consideration or provide additional justification for not addressing these CCFs.

RAI 1.12 Response

As stated in Section 6.3.1, the model for failure of an RCP seal given loss of cooling presented in CE NPSD-1199-P is for the seal for a single RCP. An SBO initiator will affect all four RCP seals while a Loss of CCW will affect one or more RCPs depending upon the specifics of the initiator. All RCP seals that lose cooling as a result of the initiator will see equivalent environmental conditional and thus are potentially subject to common cause failure. The third paragraph of Section 6.3.1 of CE NPSD-1199-P will be revised as follows:

<u>Existing:</u>
"When all seals are exposed to the same environmental conditions, the probability of multiple RCP seal cartridge failures is established assuming the RCP failure response in each seal are independent of one another (See Section 9)."

<u>Will be changed to:</u>
"When multiple RCP seals are exposed to the same environmental conditions, the probability of multiple RCP seal cartridge failures should include a common cause factor to address the potential impact of common conditions. There is insufficient data available to calculate specific common cause factors such as β, γ, and δ. Therefore, engineering judgement is used in conjunction with the available operating experience data to estimate a common cause factor, Γ, which represents the probability that all affected RCP seals fail given that one of the affected RCP seals fails.

Table 8-1 presents the operating events involving loss of seal cooling to one or more RCPs. As shown on this table, there have been only nine events involving loss of cooling to multiple RCPs. Seven of these events involved loss of cooling to all 4 RCPs (ANO2-1, ANO2-1, FCS-1, FCS-3, PV3-1, SL1-2, and SL2-3), one event involved loss of cooling to 3 RCPs (WSES3-1) and one event involving loss of cooling to 2 RCPs (SL2-2). For one of the events (SL2-3) in which cooling was initially lost to all four RCPs, cooling was restored for two of the four RCPs after about 14 minutes. The time frames for which RCP seal cooling was lost in these events ranged from 0.1 hours up to 4.5 hours. None of the events resulted in a seal failure and only two of these events involved stage failures on multiple pumps. In both events involving stage failures on multiple RCPs, the information on the stage failures is limited, but they were most likely pop-open failures for stage 3.

This data is insufficient to calculate the common cause failure factors for multiple RCP seal failures given the failure of one RCP seal, but it does provide solid evidence that failure of all seals exposed to loss of seal cooling is not guaranteed given that one fails. However, as stated above, there is a potential for common cause failure of all seals exposed to a loss of seal cooling. Because of the time dependent thermal aspects of the seal failure mechanisms, the potential for common cause failure of the seals is judged to be relatively low early in the event but will increase as the exposure time increases. Using engineering judgement in conjunction with the operating experience data in Table 8-1, the following Γ factors will be used to estimate the potential for common cause failure of all RCP seals affected by a loss of cooling event given that one seal fails:

[ ] a, c

These parameters were estimated based on the following considerations:

1. Common cause failure is possible but not assured.
2. The likelihood of common cause failure increases with the exposure time.
3. A Γ of [[ ]]a, c is a reasonable estimate for the 0 to 1 hour time frame because all nine events involving loss of seal cooling to multiple RCPs in Table 8-1 had exposure times greater than 0.1 hours and none resulted in a common cause failure of the affected seals.

RAI 1.13

The topical report concludes in Section 4.2 (pg. 4-2 ¶ 2) that each stage of an RCP must be individually evaluated because the failure mechanisms affect each individual stage differently. This conclusion may be correct, but it would then require RCP modeling to be extremely detailed and to consider or bound every possible condition that might occur for an individual stage as a result of the conditions and failures associated with the other stages, individually and in combination. Thus, the potential for cascading failures would also have to be explicitly modeled and the order of stage failures definitively described or bounded by the model. The need for this modeling is supported by the text in Section 5.3.3 (pg. 5-12 ¶ 2 and ¶ 4). However, the model does not provide this level of detail. Please clarify the intent of the stage modeling as described *in Section 4.2 and explicitly address in the model and/or failure data the increased potential for stage failures, given that other stages are already failed, or justify why the topical report does not need to address this potential.*

RAI 13 Response

The initial model considered a high probability potential pop-open relationship between stages 3 and 2. The lowermost and vapor stages are treated independently, i.e., failures in the middle seals are not propagated to either the lower or vapor seal. This feature is supported by observations of the BJ/SU and N-9000 SBO tests. By not crediting the benefit of backpressure, the model assumes pop-open potential whenever the upstream subcooling is adverse. A 50°F target is used even though experiments indicate that pop-open is not likely at that level, and if pop-open would occur at all it would occur much closer to saturated conditions. This treatment adequately models the seal failure probability for the condition when CBO is operational. The pop-open failure probability of each stage was considered the same for all stages.

For the CBO isolated condition, a constant pressure is applied to all seal stages. This results in a condition where the lower seal stages carry no load. The only seal load is felt across the vapor stage. The vapor stage will be highly subcooled as the local fluid will be at RCS pressure while the fluid temperature (depending upon the time of isolation) will be between 200 and 400°F. Thus, pop-open failure of the vapor stage is remote. So long as the vapor stage is intact, the probability of pop-open of the lower seal stages is negligible. If lower stages fail, the seal conditions are largely unchanged. If the vapor stage fails, a condition arises that was not modeled in the original report. While pop-open failures are remote, other failure possibilities exist such as failures due to existing defects or elastomer failures that would result in vapor stage bypass leakage (such as failure of the stationary face O-ring). While this does not imply a seal failure, the failure will restage the seals. Thus, the lower stages that previously were not subject to pop-open, again should be treated as if they were staged. The fault tree models in Section 6 of CE NPSD-1199-P have been revised to incorporate this failure scenario.

RAI 1.14

A footnote to Table 9.2-4 (pg. 9-14) states that, for the seals other than the BJ/SU seals, the probability of pop-open was reduced by a factor of 10 from the estimates given for BJ/SU seals because of improved design features. The justification for this reduction is not supported by any analyses. Only one N-9000 seal has been exposed to pop-open conditions (i.e., the N-9000 test). This is insufficient data upon which to support the factor of 10 reduction in value shown in the last row of the table. Were the newer seals specifically designed to have low leakages under conditions when they were not cooled? Without additional data or experience, a value much less than the existing BJ/SU seal values does not appear warranted. Please provide additional justification for this reduction factor or for a more justifiable value for the "improved" seals. This comment also impacts Tables 9.2-5a through 9.2-5f (pp. 9-16 and 9-17).

RAI 1.14 Response

Elastomer seal failures were largely attributed to deterioration of the Nitrile U-cups of the BJ/SU seals. Similar failures were not observed for ethylene-propylene sealing materials used in the RCP seals. Since no seal stage failures were attributed to these alternate materials/designs, a factor of 10 reduction was placed on the elastomer failure model. This factor is consistent with the differences in the Nitrile and ethylene-propylene survivability curves (see RAI 1.1). These curves shows that for instances where a Nitrile seal will fail, an equivalent ethylene-propylene design will require much longer to fail. (See Figure 3.4-1 of CE NPSD-1199-P.). Newer seals are also designed to ensure small at-temperature gaps that reduce the possibility for extrusion. The operating experience has been used to estimate an elastomer failure rate for seals with Nitrile U-cups (see the revised Table 9.2-1 of CE NPSD-1199-P). Based on the information in Figure 3.4-1, the failure rates for seals which used only the EP elastomers were estimated by shifting the Nitrile U Cup failure rates presented on Table 9.2-1 one time step to the right. Section 9.2.1 has been revised accordingly.

The likelihood of pop-open stage failure is also considered lower for the N-9000 seal than for its BJ/SU predecessor. Whereas the BJ/SU test indicated small leakage during the SBO test (< 0.3 gpm), N-9000 leakage was controlled to about 0.04 gpm. Furthermore, the N-9000 seal has been designed such that when the seal is static the seal faces would be divergent, thus minimizing the potential for seal leakage (Reference B1.8). Based on this, the probability of pop-open failures for the N-9000 and Sulzer Balanced Stator seals is assumed to be a factor of 2 lower than for the BJ/SU seals as is shown in revised Section 9.2.2.

RAI 1.15

Please address the following comments and questions regarding the success criteria and conditions addressed in the environmental conditions event tree presented in Section 6.1 and the associated quantification information (Chapter 9).

1. The RCP1HR top event (pg. 6-2) uses one hour to define success. However, this success criterion is not consistent with the text presented elsewhere in the topical report that indicates the RCP seals are designed to remain intact when the pumps are operated for only about 30 minutes (pg. 5-7 § 5.3.2 ¶ 2, pg. 5-13 § 5.5 ¶ 1, and pg. 7-3 § 7.1.2 ¶ 5). What evidence is there that the seals will not fail when allowed to run this long? Please justify the success criterion for the RCPs being shutdown within one hour or use a shorter time that is supported by tests and operational experience, such as within 30 minutes. Use of a shorter time would also have to be reflected in the quantification data collection.

RAI 1.15.1 Response: The top event has been clarified. The definition of this event was an attempt to simplify the modeling. The selection of one hour as the time available to trip the RCP was based on tests and operating events that indicated that seals could be operated successfully for up to 40 minutes or more. As data for RCP seal operation without seal cooling for 1 hour is not available, this event will be redefined to require tripping the RCP within 20 minutes. This is conservative for this top event because the tests and operating events have demonstrated that an RCP can operate without seal cooling for 30 to 40 minutes without failing any seal stage.

2. As implied by the text for CBO Isolation (pg. 6-2), why will the seal assembly not heat up during the top event RCP1HR? Since the seal assembly should heat up with the RCP operating for up to 1 hour, the statement regarding isolation of CBO within 10 minutes becomes moot. This event assumes that the RCPs must have already been tripped, but there is a disconnect between the timing involved in the top events. This problem demonstrates the inter-relationship between the top events of the event tree that have not been completely considered in the model. Please provide a justification as to the appropriateness of the environmental conditions individually represented by the event tree top events or revise the event tree to reflect the inter-relationship of these top events. For example, the timing could be set for both top events, RCP tripping and CBO isolation, at a time (such as 20 minutes) that supports both top events through tests and operational experience.

RAI 1.15.2 Response: The intent was that when quantified, CBO Isolated early implies that both the RCP is tripped and CBO isolated by t=20 minutes. At the end of the interval, vapor stage temperatures could reach 370°F and the other stage temperatures could be about 450 to 470°F. Tripping the RCP by this time would significantly limit seal degradation and avert pop-open as stage 3 subcooling at the Main Steam Safety Valve setpoint (~1000 psia) would be > 50°F as T_{Sat} is about 540°F.

3. The topical report states (pg. 4-6 ¶ 4) that there is potential for cascading failures as the stages heat up; with the lower stage potentially failing first due to its initially higher temperature exposure. Then, over time, the upper stages may also fail as they reach the higher temperatures. The affect of CBO isolation appears to be a slowing of the heatup rate, and thus it takes more time to reach high temperatures in the upper seals. However, based on the text, the upper seals will still reach high temperatures eventually if the accident scenario is not terminated. Assumption 2 of Section 9.2.1 (pg. 9-7) implies that the upper stages are not affected at all if CBO is isolated within 20 minutes. This assumption is also not consistent with the discussion in the last sentence under CBO Isolation in Chapter 6 (pg. 6-2), which uses a one-hour duration for isolating the CBO to define success. In the preceding paragraph of the Chapter 6 discussion, the topical report states that isolation within 10 minutes will ensure temperatures of the upper seal component are sufficiently controlled. It adds that experience has shown that failure to isolate CBO within 20 minutes will result in a significant heatup rate of all seal stages. It seems from these statements that a conservative time would be about 10 to 20 minutes for the upper stages and even less for the lower stages, but clearly not as long as one hour. By counting events greater than 20 minutes in the data, the overall number of stages exposed is increased, which in effect lowers the failure probability for each interval. Please change the criterion to reflect the above experience or provide justification for use of a one-hour duration, as opposed to a shorter time. Also, please ensure that the success criterion in Chapter 6 matches the failure data development in Chapter 9. Further, it should be explicitly stated that, for those plants that do not require the CBO isolation, this branch of the event tree should be assumed failed.

RAI 1.15.3 Response: The event tree model has been revised to reflect: (1) RCP operation for > 20 minutes without seal cooling will conservatively be assumed to result in a failure of the seal package, and (2) if the RCP is turned off and CBO isolated within 20 minutes, seal failure will be based on failure of seal stages exposed to subcooled conditions with seal stage temperatures which reflect isolation at 20 minutes. For loss of offsite power events where the RCPs are automatically tripped, isolation of the CBO can occur rapidly, so for this scenario, the fault tree models have also been quantified based on failure of seal stages exposed to subcooled conditions with seal stage temperatures which reflect isolation at 10 minutes. The HEP for this CBO Isolation timing would reflect the shorter time and plant-specific AOPs/EOPs.

4. The topical report states in Section 3.2.1 (pg. 3-5 ¶ 2) that the early CE BJ RCPs are likely to experience significant heat losses in the upper two stages, while more recent (i.e., System 80) RCP stages are well insulated. It further states that the impact of this heat loss arrangement is significant during RCP seal accident scenarios. However, it is not clear that this consideration has been taken into account in the modeling. Please clarify how this difference in specific RCP designs, including Sulzer RCPs, is addressed by the RCP seal failure model and failure data.

RAI 1.15.4 Response: The referenced System 80 RCP seals were the KSB RCP seal design; this seal design is no longer used in the United States. The three stage seal currently used at Palo Verde is expected to exhibit temperature behaviors typical of the N-9000 test, which used a three stage pump seal. The lower temperatures noted in this test included the effect of heat losses but were primarily the result of the saturated conditions that result from flashing of the high enthalpy fluid as it enters the cavity of the last seal stage.

5. It appears from the information presented (pp. 5-10 and 5-11) that, for the vapor stage, the temperature is actually higher if the CBO is isolated late as opposed to not being isolated at all. Please explain what is meant by "late" (i.e., how much time after the LOCCW makes its isolation late). Also, please explain how this condition is reflected in the model since the model only addresses isolation within one hour or not. (In other words, it does not differentiate between late isolation and no isolation though there is a difference in conditions apparent for the vapor stage).

RAI 1.15.5 Response: See responses to RAI 1.3 and to item 1.15.4 above.

6. End states RCPF-9 through RCPF-16 reflect the condition in which CBO isolation does not occur within the first hour. As such, these end states should have a more rapid heatup of the upper seal stages then the other end states (i.e., RCPF-1 through RCPF-8), leading to earlier and more likely failure of the upper stages. However, Chapter 9 (e.g., Table 9.3-1, pg. 9-22) does not show any differences in some of these probabilities for similar scenarios (e.g., RCPF-13 and RCPF-5). How is this conditional difference reflected in the model and the quantification?

RAI 1.15.6 Response: The elastomer failure probabilities presented in Table 9.3-1 were based on the operating experience data presented in Table 9.2-1. CBO was not isolated for all but one event presented in Table 9.2-1; the event where CBO was isolated was the Palo Verde test and lasted only 0.6 hours. Thus, the elastomer failure probabilities used in Table 9.3-1 are representative of the "CBO Not Isolated" condition and as such the quantification for endpoints RCPF-1 through RCPF-8 is conservative. Section 9 been revised to clarify the quantification of the model. (See also the responses to RAI 1.18.) The revised Section 9.2.2 explicitly defines each value used in the quantification of the model for each seal design. Tables 9.3-1, 9.3-2 and 9.3-3 have been restructured to make the quantification easier to see and to provide explicit pointers to Section 9.2.2 for each value used.

7. The conditions reflected by the end states are very specific to the top events and will differ considerably based on the assumptions in the model. As an example, RCPF-1 reflects the condition in which the RCP may have operated for up to one hour after the event, the CBO may have been left unisolated for up to one hour after the event, the RCS may have been just 50°F subcooled, and the seals may have had a thermal exposure of up to one hour. It does not appear that these worst-case conditions are used to establish the conditions experienced by the RCP seal stages. Are these conditions used to determine the probabilities of survivability of the seal stages for this end state or was a less severe condition assumed? If the latter, please ensure the event tree success criteria are consistent with the event tree modeled conditions and resulting end states.

RAI 1.15.7 Response: As noted above, the model has been revised to change the timing for tripping the RCP and isolating CBO. Furthermore, the definition of the endpoints has been revised to facilitate implementation of the updated pop-open model as shown by the revised event tree, attached. Also, as noted in the response to item 6 of this RAI, Section 9 has been revised to clarify the quantification of the model. The revised Section 9.2.2 explicitly defines each value used in the quantification of the model for each seal design. Tables 9.3-1, 9.3-2 and 9.3-3 have been restructured to make the quantification easier to see and to provide explicit pointers to Section 9.2.2 for each value used.

RAI 1.16

Please address the following comments and questions regarding the modeling and conditions addressed in the RCP seal failure/leak model presented in Section 6.2 and the associated quantification information (Chapter 9).

1. The fault logic model in Chapter 6 (pp. 6-8 and 6-11) contains the potential conditional pop-open failure of stage 2 due to the failure of stage 3, but it does not include the potential for stage 2 to independently pop-open. Likewise, Table 9.2-3 (pg. 9-12) does not address the potential for an independent failure of the second stage (P02) in addition to it being coupled with the third stage (P03). Both potential events (i.e., coupled failure and independent failure of P02) need to be addressed in the model and reflected in the data because both events could occur. This comment also impacts Tables 9.2-5a through 9.2-5f (pp. 9-16 and 9-17).

RAI 1.16.1 Response: Given a loss of seal cooling with CBO not isolated, the first stage seal will have more than 100°F subcooling, the second stage seal will have just over 50°F subcooling and the third stage seal will have just under 50°F subcooling. The vapor stage is not subcooled but the pressures are not high enough to challenge the seal as shown by operating events. Thus, operating events demonstrate that the third stage is the stage most likely to pop-open or fail. Given failure of stage 3, the subcooling for stage 2 will be reduced thereby increasing the likelihood that stage 2 will pop-open, as represented in the model. The independent pop-open failure for stage 2 is about two orders of magnitude lower and would still require a failure of the third stage before a seal failure could occur. The failure of stage 3 does impact the subcooling for the first stage or the vapor stage so there is no coupling between a failure of the third stage and failure of the first stage.

Failure of the first stage due to pop-open or any other mechanism would increase the subcooling for both the second and third stage and thus reduce their potential for pop-open failures. This beneficial coupling was not modeled.

Likewise, a failure of stage two for any reason would increase the inlet pressure to and hence the subcooling for the third stage. Again, this beneficial coupling was not modeled. With CBO not isolated, failure of the vapor stage would not affect the subcooling of the lower stages so there would be no coupling to the failure potential of the lower stages.

2. The "Impact of Failure Mechanism on Stage" column (pp. 4-18 and 4-19) indicates that, for every stage except the vapor stage, there should be no cause for pop-open if the CBO is isolated. However, this does not seem consistent with the model and Condition 2 of Section 9.2.3 (pg. 9-12), which applies to the specific condition of the CBO being isolated and the RCS being saturated. Please explain this inconsistency.

RAI 1.16.2 Response: When CBO is isolated, there is no flow through the seal stages. The entire pressure drop is taken across the vapor stage so there is no pressure drop across the first, second or third stages. Given that the pressure is the same on both sides of the first, second and third stages, there is no potential for a pop-open of these stages. However, should the fourth stage fail, flow through the lower stages will be re-established and they will re-stage. These stages will then be subject to pop open as represented in the model. In essence, the model assumes that stage four fails first.

3. It is stated in Section 6.2.2 (pg. 6-5 ¶ 1) that there is an increased potential for the second-stage seals to pop-open in the 3-stage model as compared to the 4-stage model, but this does not seem to be reflected in the numbers presented in Chapter 9 (pp. 9-22 through 9-24). How is this increased potential for pop-open failure reflected in the model?

RAI 1.16.3 Response: For a loss of seal cooling event with CBO not isolated, subcooling of the first stage is governed by the subcooling of the RCS cold leg and is not affected by the condition of the stages above it. The second stage in three stage seal design has less subcooling than the second stage in the four stage seal, but it is still slightly greater than 50°F. Failure of the second stage would not affect the first stage and would increase the subcooling of the third stage. If the third stage fails, the subcooling in the second stage will become slightly less than 50°F and thus would become subject to pop-open. In the revised model, the second stage in the three stage seal design is modeled like the third stage seal in the four stage seal design. Sections 6 and 9 of CE NPSD-1199-P have been revised extensively in response to these RAIs. Table 9.2-12 of the revision summarizes the event data used to quantify the probability of pop-open failures.

4. The potential for conditional pop-open failure of a stage is only applied to stage 2, which is dependent upon stage 3 failure. Why are the other stages not likewise dependent? For example, if stage 2 fails, why doesn't this cause the potential for increasing the failure likelihood of stage 1, or stage 4 failure causing the failure of stage 3? In particular, there seems to be an inconsistency between the 3-stage model and the 4-stage model in this regard.

RAI 1.16.4 Response: See response to item 1.16.1 above.

5 The discussion in Section 9.1 (pg. 9-2 ¶ 2) on the coupling of stages 2 and 3 is tied to the CBO not being isolated. Please justify why this coupling cannot occur when CBO is isolated. Absent such justification, please explain the impact of the possible condition on modeling and failure data development.

RAI 1.16.5 Response: When CBO is isolated, there is no flow through the seal stages. The entire pressure drop is taken across the vapor stage so there is no pressure drop across the first, second or third stages. Given that the pressure is the same on both sides of both the second and third stage, there is no potential for a pop open and thus no coupling of the potential for pop-open failure between stages 2 and 3 when CBO is isolated.

RAI 1.17

Chapter 10 of the topical report provides two sample cases. However, these cases are very narrowly focused and contain a number of simplifying assumptions. These cases do not demonstrate the utility and complexity of the CEOG RCP seal model, and they raise questions regarding the assumptions used in the sample. For example, why is it assumed that the operators trip the RCPs instead of using a human error probability estimate for this branch probability? Why is recovery limited to four hours instead of over the whole mission time, which may vary? Why is the RCS assumed subcooled? What is the impact if there is a common cause CCW dependency? These unanswered questions lead to the conclusion that the full and proper use of the CEOG RCP seal model is not clearly presented. A complete sample application that shows its use in a plant's PRA, with step-by-step results, should be provided to better demonstrate the utility and complexity of the model, use of the data, and integration into a PRA.

RAI 1.17 Response

The first paragraph of Section 10.0 states that the calculations are illustrative only; they were not intended to represent any plant or group of plants, nor their PRA models. The model presented in Section 6.2 is for failure of a single RCP seal given loss of cooling to that seal. This model is intended to be inserted into a given utility's PRA model to cover the potential for RCP seal failure for sequences that would result in loss of cooling to one or more RCPs. As illustrated by the event tree model presented in Figure 6.1-1, the potential for failure of an RCP seal given loss of seal cooling is influenced by plant conditions and actions associated with the sequences of interest. The exact status of plant conditions, their associated probabilities and the potential for human actions are highly dependent on the sequence of interest and are plant specific. As with all other aspects of the overall PRA, it is the responsibility of the utility to determine all sequences where this model is required and to properly identify the associated plant status at the time of occurrence for each specific sequence and for properly determining the appropriate human actions and HEPs. The sample calculations are illustrative only and were deliberately kept at a high level to avoid the appearance that they represented a complete calculation.

RAI 1.18

The following attachment provides typographical, editorial, consistency, clarification, and calculational comments on the topical report. Please address these items in the revision to the topical report. A formal response to them as part of the response to the RAI is not required or desired, except for those with which the CEOG may disagree.

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
General	*The topical report uses the word "stage" as a subcomponent of a RCP "seal." However, there are numerous places throughout the topical report where "seal" is used when "stage" is intended. To a lesser degree there are places where "stage" is used when "seal" is intended. These inconsistent uses of these words need to be corrected so that the proper meaning is conveyed.*
Response	Text was revised as appropriate throughout report.
pg. 3-4 ¶ 3	*The topical report states that the CBO water flows at a rate of 0.6 to 1.5 gpm during normal operations, but Table 3.2-1 (pg. 3-3) shows a design flow rate of 1.0 to 3.0 gpm for various plants (1.0 to 1.5 gpm without CE System 80 RCPs), with low and high flow rate alarms ranging from 0.75 to 6.0 gpm (0.75 to 2.25 gpm without CE System 80 RCPs), respectively. Also, these values differ from those presented in the CBO definition (pg. 2-1). Please clarify these apparent inconsistencies.*
Response	The text was revised to be consistent with Table 3.2-1.
pg. 3-5 § 3.2.1	*The topical report states in that all RCP seal stages are designed to seal at 2500 psig with the pump stationary. However, it is possible that the seal stages are designed to seal at 2500 psig when the seal stages are cooled and that they may not be designed to seal at 2500 psig when the seal stages are not cooled. Please clarify the conditions under which the pumps are designed to seal at 2500 psig.*
Response:	The seals are designed for 2500 psig and [[ ]]^{a,c}. Elastomers have been demonstrated to survive at a pressure of 2500 psig and [[ ]]^{a,c}. (See RAIs 1.1, 1.2 and 1.3) The N-9000 test demonstrated the integrity of the vapor stage under SBO conditions at a pressure of 2500 psig.
pg. 3-9	*The Table 3.3-1 flow capacity entry for Arkansas 2 is not provided.*
Response	The CBO isolation line relief valve flow rate is 22 gpm. This value has been added to Table 3.3-1.
pg. 3-10	*Figure 3.3-1 misidentifies the third RCP as RCP 4; it should be RCP 3.*
Response	Figure 3.3-1 was corrected.
pg. 4-1 § 4.1 ¶ 1	*This section divides RCP seal failures into three categories. Please clarify how each of these failure categories is reflected in the RCP seal failure model in Chapter 6. If a category is not reflected, please provide a justification for why this category of failures does not need to be considered in the RCP seal failure model.*
Response	Section 4.1 provides a discussion of operating failures encountered during the early years of plant operation to indicate the type of problems that lead to concerns about RCP seal reliability. The model presented in this report is for RCP seal failure given loss of seal cooling. The other operational failure mechanisms are addressed only implicitly in the model to the extent that they could contribute to the potential for a pre-existing stage

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
	failure or a random stage failure.
pp. 4-4 & 4-5, 4-8 - 4-15, and 4-18 & 4-19	*These tables provide qualitative information regarding the impacts of various conditions and failure mechanisms on the stages, but it is not clear how this information is reflected in the RCP seal failure model. It does not appear that the model explicitly addresses all the potential impacts and conditions identified in these tables. Please explain how the information presented in these tables was used in developing the RCP seal failure model. If some impacts are not reflected, please provide the justification for ignoring these potential impacts. Further, it would be helpful in understanding the impacts better if some quantitative information (e.g., resulting leakage flowrate) was also included in these tables.*
Response:	The information presented in Tables 4.2-1, 4.2-2 and 4.2-3 is a qualitative evaluation performed prior to the development of the model and provides supplementary background information. This information is not used directly in the model. The model reflects the key failure mechanisms described in Reference B1.6. The RCP seal stage model lumps binding and elastomer failure together. Failure probability is based on test data and event observations. Leakage information is contained in Tables 5.2-1 and 5.2-2.
pp. 4-6 ¶ 2 and 4-16 ¶ 2	*These paragraphs identify the potential inter-relationships between different failure mechanisms of RCP seal stages, which do not appear to have been reflected in the follow-on tables, the RCP seal failure model in Chapter 6, or the quantification in Chapter 9. Please explain how the model reflects how one failure mechanism on one stage may directly lead to or contribute to a different failure mechanism in another stage. If these failure mechanisms are treated as independent events, please justify this treatment, especially in light of its apparent inconsistency with these paragraphs.*
Response:	With regard to page 4-6, ¶ 2, the impact between binding and pop-open was considered appropriately by treating pop-open as an unrecoverable process. That is, if all seal stages fail, a LOCA is initiated and restoration of CCW was not considered as a mechanism for terminating the LOCA. Recovery of power/CCW following the initiation of a LOCA is considered as a recovery mechanism to the extent that recovery of CCW and power permits mitigation of the LOCA. Recovery of power/CCW prior to failure of all seal stages is considered to preclude the LOCA because the intact stages will remain intact.
Pg. 4-7 ¶ 2	*The concluding sentence of this paragraph is ambiguous. Are there any BJ or Sulzer seals in use that do not utilize "qualified seals constructed of ethylene propylene" (i.e., potentially containing Nitrile compounds)?*
Response	At the time the original report was prepared, Fort Calhoun had the original BJ/SU seals with Nitrile cups. However, Fort Calhoun installed Flowserve N-9000 seal packages on all RCPs during their May 2002 refueling outage.
pp. 5-2 & 5-3	*Table 5.2-1 refers to plant-specific Table 5.2-3 (pg. 5-3) for two conditions, but Table 5.2-3 only addresses the catastrophic failure of all RCP seal stages. Do these leakage rates also apply to the conditions when the vapor seal is intact, but the other stages are failed catastrophically? If not, please provide the additional leakage rates for this condition directly in Table 5.2-1 or explain how it is addressed in the model, or, if it is plant-specific, provide another table to present this information.*
Response	The fourth entry in Table 5.2-1 is somewhat misleading. If all three lower PBDs failed catastrophically and the vapor stage is intact, the CBO flow would be limited by one of 3 factors. If CBO is fully isolated, the leakage flow would be limited by the leakage through the intact vapor stage seal, which would be small. If CBO is not isolated, then the CBO flow rate would be limited by the flow limiting check valves which, depending on the

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
	plant, will limit flow to between 10 and 15 gpm. If CBO flow is not isolated and the excess flow check valve fails, the values in Table 5.2-3 would bound the absolute maximum possible leakage rates because these values represent the maximum possible flow through the RCP thermal barriers and into the seals. Table 5.2-1 has been updated accordingly.
Pg. 5-6	*What is the source of information for Table 5.3-1 and 5.3-2a?*
Response	The information contained in these tables is a composite based on observations from BJ/SU SBO and LOCCW tests (References B1.1 and B1.2, respectively) and seal stage hydrodynamic characteristics. That is, the BJ/SU SONGS LOCCW tests indicated seal heatup such that 10 minutes after the onset of the event, the seal stage temperatures vary from 250°F for the vapor stage to 300 – 350°F for the lower stages. For SBO conditions (RCP off), a somewhat slower heatup would be expected. It was assumed that when CBO is isolated early, the temperature distribution in the seal would be relatively low and well below saturation conditions. The 1000 psia system pressure is based on the steam generator set-point pressure (Tsat ≈540°F). When CBO is isolated, this pressure is applied to all stages. The CBO isolated late case is based on both BJ/SU tests. Extended heatup would allow temperatures to reach a near equilibrium condition with the lower stages at 515°F to 525°F and the vapor stage around 400°F (see attached Figures B1.2-1, B1.2-2 and B1.2-3). Late isolation does not avert heatup of the stages. However, with late CBO isolation, the seal de-stages due to the loss of flow through the PBDs and all stages see the same pressure. Under these conditions, the vapor stage provides the final seal. Under the temperature and pressure conditions associated with the late CBO isolation, the vapor stage has sufficient subcooling to preclude the potential for seal stage pop-open failures. The CBO not isolated case is based on observations in the FPL BJ/SU SBO test. Variations in the vapor stage pressure were observed during that test. The point used in the vapor stage assessment was assumed to be slightly above the typical VCT pressure of ~ 50 psig and the stage was assumed to be saturated. In the 70 hour test, conditions in this region varied from 50 to almost 700 psi and temperatures from 250°F to 400°F.
.	*What is the meaning of the last line of Table 5.3-3, "RCS Pressure for RCP to Reseat"?*
Response	The RCP has upper and lower stops to limit shaft motion. When the plant is shutdown, the RCPs sit on the lower stop. At the plant starts up and increases pressure, there is a point at which the system pressure offsets the weight of the RCP motor, so that as the pressure increases, the pump shaft moves upward towards the upper stop. During normal operation at normal system pressure (~2250 psia) the pump operates with the shaft at or near the upper stop. As the plant shuts down, the reverse process occurs so that when the system pressure drops below the point at which it just matches the downward force due to gravity acting on the pump motor, the whole assembly will reseat on the lower stop and there will be no further downward motion.
pp. 5-10 & 5-11	*What is the source of information for Tables 5.3-4a, 5.3-4b, 5.3-4c, 5.3-5a, 5.3-5b, and 5.3-5c?*
Response:	See response to question about Tables 5.3-1 and 5.3-2A (above). Temperature data is extrapolated from BJ/SU SBO/LOCCW tests (references B1.1 & B1.2 respectively). Also note that for the CBO not isolated cases, stage pressures are based on fully operational PBDs and nominal CBO flows. In the 4-stage seals, the PBDs produce equal stage pressure drops.

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
Pg. 5-11	*The CBO Isolation Early Temperature entry for Seal Cavity 1 is not provided in Table 5.3-5a.*
Response	The temperature should be 300°F. Table 5.3-3a has been revised.
Pg. 5-13 & 5-14 § 5.6 ¶ 1	*How is this information on RCP motor performance utilized in the RCP seal failure modeling? It appears from the text that some utilities have postulated or assumed that the RCP motors fail on a LOCCW, thus eliminating the potential for a RCP to operate during these events. However, as this section indicates, that assumption is not supported by the events and experimentation. The assumption essentially is taking credit for an assumed beneficial failure to avoid a worse situation. As presented, this assumption is not appropriate and should be corrected in existing models that use it to avoid having to address the continued operation of RCPs during a LOCCW.*
Response	The information in Section 5.6 ¶ 1 is not directly used in the RCP seal failure model. Section 6.2 presents the model for failure of an RCP seal given loss of seal cooling and Section 6.1 presents an event tree which delineates the environment conditions which impact the quantification of the seal failure model. As can be seen from Figure 6.1-1 and the associated discussions, one of the key factors that influences the failure likelihood of the seal is whether or not the RCP has been tripped. When a utility incorporates the seal failure model at the appropriate places in their PRA, they are responsible for determining the appropriate environmental conditions and for establishing the appropriate split fractions for each of the key environment conditions discussed in Section 6.1. With respect to tripping the RCP, the split fraction would be 1.0 for loss of offsite power while the split fraction for a loss of CCW event would typically be based on the probability that the operators would trip the RCPs in time given the loss of CCW. Failure of the RCP motor itself as a direct result of the loss of CCW had also been postulated as a way in which the pumps might be stopped. (Note that this would be considered a consequential failure, not a "beneficial" failure.) Section 5.6 discusses this mechanism and provides evidence that the pump motor would most likely not fail within the time frame of interest. While it is still the utility's responsibility to select values appropriate for their plant, the following sentence has been added to the end of the first paragraph in Section 5.6, as revised: "Given this information, utilities should not credit failure of the RCP motor as a means of stopping the RCP given loss of CCW unless they have documentation that loss of cooling to the pump motors will result in failure of the motors within the time frame of interest for their RCPs."
Pg. 6-3 *§ T-EXP*	*This breakdown of exposure times seems very detailed, without any apparent corresponding benefit. It seems the model could be greatly simplified if the thermal exposure categories were reduced to two (e.g., thermal exposures less than 1 hour and exposures greater than 1 hour)?*
Response:	The breakdown of exposure times is based on typical battery depletion times and offsite power recovery times used in most SBO PRA models. These exposure times are needed to support the recovery analyses.
Pg. 6-4	*For the last column, T-EXP (Thermal Exposure Time), the event tree branches leading to the identified end states "all" only represent the failure branch for the individually identified time exposure intervals. Each branch under T-EXP should also reflect a success branch, or this top event could be expanded to reflect the progressive success and failure paths. For example, the event tree could include top event T-EXP1 (success or failure of stage within first hour of exposure), then top event T-EXP2 (success or failure of stage during second hour of exposure if it survived the first hour) and so on.*

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
Response:	Based on this question and the revised treatment for pop-open failures, the model was revised to address five integral time frames; 0.1 to 1 hour, 0.1 to 2 hours, 0.1 to 4 hours, 0.1 to 8 hours and 0.1 to 24 hours. See Section 6.1, Figure 6.1-1 and Tables 9.3-1A through 9.3-3F.
Pg. 6-5 § 6.2.1 ¶ 2, pg. 9-11 § 9.2.2 ¶ 1, and pg. 9-20 § 9.2.5	*It is not clear why the pre-existing seal stage failures are limited to one RCP or why there could not be more than one stage failure in a given year. It seems that plants could operate with a degraded or failed stage on multiple RCPs or that multiple failures could occur throughout a year, especially if considering the potential for design/manufacturing errors. Either the potential for multiple pre-existing failures, including manufactured defects, should be included in the model, or a justification for why this condition cannot occur should be presented. Further, the text in Section 9.2.5 should clearly indicate the rationale for assuming that there cannot be a pre-existing failure at the startup of the plant to support its calculation at the end of this section that uses a 0.5 multiple with the year.*
Response:	As discussed in Section 9.2.2 of the report, the assertion that an operating plant could expect to experience one operating RCP seal stage failure per year on average was based on a brief review of recent plant operating experience. This information indicated that CE plants see one or fewer stage failures in any given year. The model, therefore, assumed that there would be one stage failure event per year per plant. The likelihood that a given stage would be the stage that failed is 1/16 except for Palo Verde which would be 1/12.. Given that a specific stage does fail, that failure can occur anywhere in time, from T=0 to T=1 year, with equal likelihood. Thus, the plant could run with a failed stage for anywhere from a full year to essentially no time. The potential challenge (the loss of seal cooling) also occurs randomly in time so, on the average, the probability that the stage failure occurs before the challenge is 0.5. The pre-existing stage failures on a given pump are treated as mutually exclusive because a plant will shutdown should a second stage fail on a given pump. Thus, the window of exposure for multiple pre-existing stage failures on a given pump would be extremely small. As previously discussed, the seal failure model presented in CE NPSD-1199-P is for a single seal package only. When this model is incorporated in the plant PRAs, the plant must account for the fact that the output of this model is the probability that a specific seal will fail and that the overall probability must reflect that this failure could occur on any one (or more) of four RCPs. This is done by multiplying the base probability by four to account for all of the RCPs. The text in Section 9.2.5 points to Section 8.1.2. This section does not exist. The text has been modified to point to Section 9.2.2.
Pp. 6-7 & 6-8	*The "RCP Stage 2 Fails" gate should be SF003, not SF002.*
Response:	Figure 6.2-1 has been modified to address this issue as well as the issue discussed in the next item.
Pg. 9-2 § 9.1 ¶ 1	*The equation's nomenclature is not consistent with the fault tree nomenclature (pp. 6-7 – 6-11). To avoid confusion, the nomenclature should be made consistent.*
Response:	The equation on page 9-2 has been revised to read as follows: $$\text{Probability of RCP Seal Failure} = \prod_{N=1}^{N = \text{total stages}} (SF00N)$$ Figure 6.2-1 has been also been revised so that the gate names reflect the appropriate seal

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
	stage consistent with the equation on page 9-2. (See response to previous item.)
pg. 9-9	*The entry for event FCS-2 for the duration between 1 and 2 hours should be blank, not 12, and the ensuing calculations in this column should reflect this change.*
Response:	Table 9.2-1has been revised.
Pg. 9-11 § 9.2.2 ¶ 1	*The parenthetical calculated λ does not include the apparent consideration of the number of stages at a plant. The equation is also incorrectly shown. Based on the presented information, the random stage failure rate should be:* λ = *(1 stage failure/16 total stages) / (1 year * 8760 hours/year * 0.75)* = *9.5E-6 failures/hour*
Response:	Section 9.2.2 and Table 9.2-2 have been revised. Note that the time interval 0 < T < 24 hrs was also added to provide coverage for longer time intervals.
Pg. 9-11 § 9.2.2 ¶ 2	*The estimated random seal degradation value for PVNGS does not include the 0.75 plant availability factor as used for the other plants. This would increase the degradation rate to:* λ = *(2 stages degraded/36 stages) / (6 years * 8760 hours/year * 0.75)* = *1.4E-6 degraded/hour*
Response:	Section 9.2.2 and Table 9.2-2 have been revised.
Pg. 9-11	*The last column in Table 9.2-2 is not based on a 24-hour mission time, but rather, uses a calculation time of 10 hours. This column should either use a 24-hour mission time or justify the use of a shorter time. In either case, the text should state that the plant-specific implementation needs to assess the appropriateness of the mission time used in this column and to adjust the failure rates accordingly.*
Response:	The time interval 0 < T < 24 has been added to Table 9.2-2.
Pg. 9-12 ¶ 2	*The concluding paragraph ends with the statement that only events where CBO was not isolated were assumed to contribute to the failure mode of pop-open, but then the conditions identified below this paragraph involve the condition when the CBO is isolated. This apparent discrepancy needs to be clarified.*
Response:	The sentence refers to the selection of data used to quantify pop-open failures. Even though pop-open is not considered credible given a high degree of subcooling, a failure probability of 0.001 was applied. Section 9.2.3 has been modified to discuss pop-open failures.
Pg. 9-18	*In Table 9.2-6a, the probability of failure for the third stage is supposed to be the same as for the prior Table 9.2-5c per the preceding text (pg. 9-18), but the "less than one hour" entry is an order of magnitude lower. Likewise, the third stage entries in Table 9.2-6b are not consistent with those of Table 9.2-5d, and the third stage entries in Table 9.2-6c are not consistent with those of Table 9.2-5f. Please correct these inconsistencies.*
Response:	These tables have been restructured based on a re-review of the data.
Pg. 9-19	*The text indicates that saturation conditions are assumed to exist at all stages and that this is conservative for the fourth-stage vapor seal, but then the fourth-stage entries in Tables 9.2-7a through 9.2-7c (pg. 9-19) use the values derive for subcooled conditions instead of the values derived from the data, which are supposedly associated with saturation conditions. Please correct the inconsistency between the text and the resulting tables.*

RAI-18 EDITORIAL AND CLARIFICATION COMMENTS

Reference	Comment
Response:	Vapor stage performance is unique. During LOCCW or SBO events, vapor stages, when CBO is not isolated, operate under low pressure saturated conditions. BJ/SU seals have been operated 50 – 70 hours under CBO not isolated conditions without experiencing pop-open. Also, in the events and tests where the vapor stage was exposed to SBO conditions, no pop-open event has occurred. Based on the positive past performance and the less adverse operating conditions, vapor stage pop-open was treated as a low probability failure. In the case of the N-9000 seals, this is further supported by their observation based on structural analyses which indicates that under "static" SBO conditions, the seal stage faces would be divergent and not subject to pop-open.
Pg. 9-19	*Table 9.2-7c third-stage entries are stated earlier in the topical report (pg. 9-17) to be one-half the improved seal stage value for this stage. However, this entry is only one-third the value. Please correct or explain this inconsistency.*
Response:	These tables have been restructured based on a re-review of the data.
Pg. 9-20 § 9.2.5	*It is not clear why credit is taken for plant availability in the calculation in Section 9.2.5, as it is not contingent on the operation of the plant to determine the time to failure. Please remove the availability factor from the equation and revise the calculation.*
Response:	The calculation has been revised as shown in Section 9.2.5.
pg. 9-25	*Table 9.3-4 should include end state RCPF17 so that the sum of the end states equals one.*
Response:	The event tree and fault tree models in Section 6 of the topical have been revised in response to these RAIs. Endpoint RCPF17 has been renamed as RCPF21. RCPF21 represents guaranteed failure of the RCP seal given that the RCP is not tripped within 1 hour. The probability of this endpoint would be calculated using plant specific HEPs for the top event "RCPs Secured within 20 Minutes." The conditional seal failure probability given failure to secure the RCPs is 1.0. This is equivalent to the other conditional seal failure probabilities presented in Table 9.3-4. The other top events in the event tree also require plant-specific failure probabilities which are not within the scope of this report.

B.2 Response to NRC Request for Additional Information Concerning CE NPSD-1199, Rev 0, "Model for Failure RCP Seals Given Loss of Seal Cooling," dated July 24, 2003

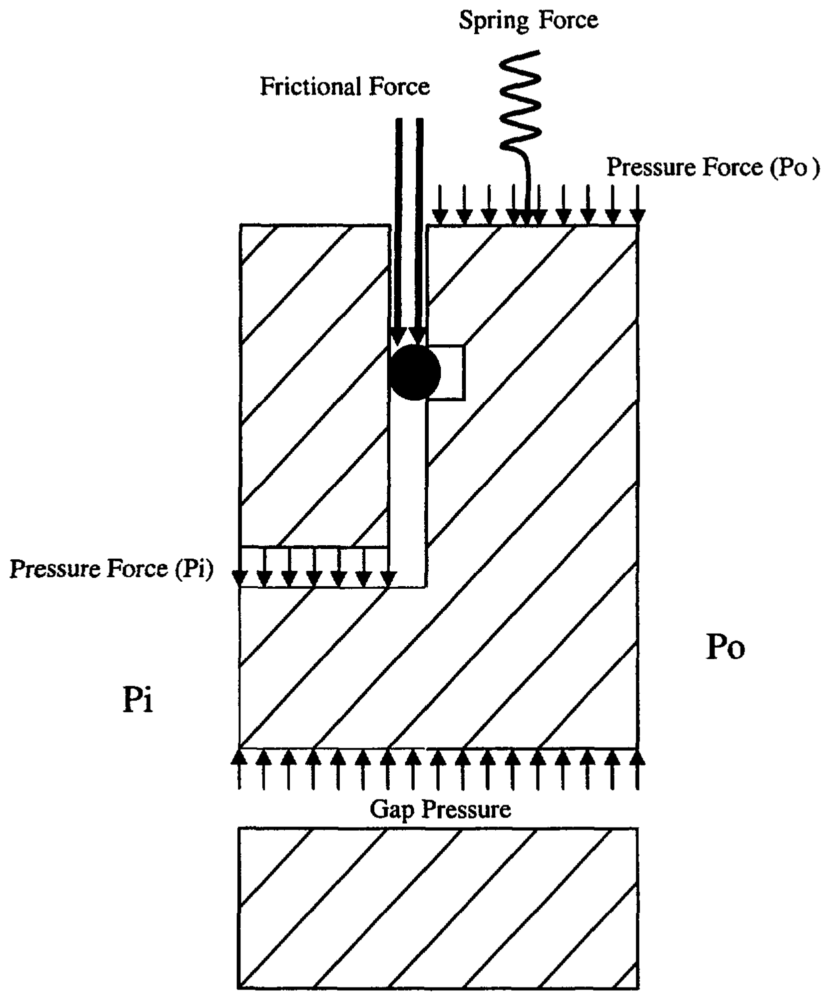
RAI 2.1

In the response to staffs request for additional information RAI 16 (page 36 of the responses to the RAIs), it is mentioned that when the controlled bleed-off (CBO) is not isolated, the inlet fluid to the vapor seal is not subcooled, but the pressures are not high enough to challenge the vapor seal. However, according to Table 5.3-2a of CE NPSD-1199, the outlet pressure to the vapor seal is less than one-half the inlet pressure to the vapor seal. Thus, neither of the conditions which would ensure the stability of the vapor seal are present and the seal may pop open. Data was discussed in the response to RAI 2 (page 4 of the responses to the RAIs) which indicated that in tests the vapor seal did not pop open. However, there is no subcooling in the case where the CBO is not isolated (fluid is at saturation conditions), so the test results may not be applicable. How then is the probability of failure for the vapor seal, (used, for example, in Table 9.2-15A of the revised Section 9 given in the responses to the RAI) justified?

RAI 2.1 Response: Evaluation of seal events on CE PWRs indicates that the middle seal stages are the more likely to experience "pop-open." While small leakages may be observed through the vapor seal, no catastrophic failure has been noted. Although detailed thermal-hydraulic behavior could not be confirmed for most of these events, it is expected that vapor seal operation was in or near saturation for conditions where CBO was not isolated. Experimental data with CBO operation is limited. However, tests conducted by Byron-Jackson for the loss of component cooling water (Reference B2.1) and for station blackout (Reference B2.2) seal performance also indicated periods of two-phase and near two phase conditions in a vapor seal while seal leakage remained small (< 0.5 gpm). Specifically, the RCP seal cartridge was operated for a period of 30 minutes without seal cooling in one loss of coolant test. The seal cartridge remained operational and the controlled bleedoff (CBO) was not isolated during the test interval. A review of the seal temperature and pressure data indicates a period of ~10 minutes where the vapor cavity was nearly saturated (within ~10°F of saturation) or saturated. Vapor seal leakage measurements conducted at the time indicated seal leakage of less than 0.26 gpm. No "pop-open" behavior was observed, even though the backpressure to vapor seal cavity pressure ratio was much less than one half. The total upward force (F_{up}) exerted by the fluid in the seal gap was compared to the total downward (restorative) force (F_{tot}) acting on the RCP seal upper face for the N-9000 seal design. This comparison demonstrated that at these lower absolute pressure conditions the upward force generated in the seal by the seal leakage is insufficient to overcome the downward seal force and hence the seal would not "pop-open."

The conceptual seal design is presented in Figure B2-1. The downward force is a result of the combined upstream and downstream pressure loads on associated areas, friction and spring load. The upward (or opening) force is based on the fluid pressure in the seal gap. The capability of the seal to remain closed under a pressure differential is based on a balance between the total downward force (F_{tot}) and upward gap pressure force (F_{up}) assuming that the pressure of a two-phase mixture results in a critical flow condition in the seal gap.

Figure B2-1: Idealized RCP Seal Stage Force Balance



Results of the evaluation are summarized in Figure B2-2. At pressures up to [[ ]]^{a,c} (backpressure rates of [[ ]]^{a,c}) the net seal downward load is sufficient to maintain the vapor seal stage integral.

Based on this force comparison, it was concluded that at low upstream RCP seal pressures (at least up to [[ ]]^{a,c} psia), the functional capability of the RCP seal vapor stage is assured despite the fact that the seal back pressure is less than 50% of the upstream pressure (a rule of thumb to estimate seal stability).

Figure B2-2: Comparison of F_{tot} and F_{up} for Typical N-9000 Design

a,c

RAI 2.2

On page 117 of the response to the RAIs, it is stated that when CBO is not isolated and the reactor coolant system (RCS) is saturated that stage 4 is relatively subcooled. This is at variance with the statement made in the response to RAI 1.16, referred to in question 2.1 above. According to Table 5.3-2a of CE NPSD-1199-P, the inlet conditions to the vapor seal are saturated conditions. There is no subcooling. Please explain this apparent contradiction.

RAI 2.2 Response:

There is no subcooling in stage 4. The reference text (p117 of Reference B2.3) should state that when the CBO is not isolated and the reactor coolant system (RCS) is saturated that stage 4 is relatively saturated. This statement will be corrected.

The example below supports this by showing that the stage 4 pressure is low. At these low pressures, the quality of the mixture in the cavity is relatively low, about 0.2.

Example calculation of mixture density for h_o = 490 Btu/lbm, P_{sat} = 70 psia.

Initial conditions: h_o = 490 Btu/lbm
h_f = 272.7 Btu/lbm from steam tables (Reference B2.4)
h_{fg} = 907.8 Btu/lbm (Reference B2.4)
υ_g = 6.2 ft3/lbm (Reference B2.4)
υ_f = 0.0175 ft3/lbm (Reference B2.4)

Quality is found:

$$X = \frac{h_o - h_f}{h_{fg}} = 0.239$$

RAI 2.3

Table 5.3-2a of CE NPSD-1199-P, for post-accident conditions following a station blackout (SBO) event, gives the pressures and temperatures at the inlets to the various seal stages. Consider the case where the CBO is not isolated. Here, the pressure is assumed to drop uniformly across the first three seal stages. The pressures given in Table 5.3-2a of CE NPSD-1199-P are based on the assumption of a uniform pressure drop across the first 3 stages. This is a reasonable assumption for normal operation. However, as several stages will experience two phase conditions, the pressure drops in the pressure breakdown devices will be influenced by flashing. This is particularly significant for those seal stages that appear to indicate the presence of a superheated condition. Under these conditions the pressure drop across the various seal stages will not be uniform. Likely, the flow resistance will be greater where saturated and supersaturated conditions occur. The flow model has to take into account the flashing of the water in the pressure breakdown devices and controlled bleed-off line. Once the pressures are recalculated, the probability of seal failure may change, and the applicability of loss of seal cooling events may be affected. Please analyze.

RAI 2.3 Response:

The pressure distributions presented in Table 5.3-2a as with the other related tables indicated "representative" seal stage pressures and subcooling. Regardless of the displayed subcooling, the "pop-open" failure probability for the internal seal stages (seal stages 2 and 3) was set assuming that both internal stages were saturated and subject to "pop open."

A limited scope analysis was performed to demonstrate the impact of two-phase flow through the seal pressure breakdown devices (PBDs) and controlled bleedoff (CBO) line. The intent of the calculation was to predict the impact of the emergence of two-phase conditions on the RCP seal stage pressure distribution and the pressure drop in the CBO line. The calculation assumes the CBO line is not isolated and the enthalpy losses of the liquid in the seal are negligible. The RCP seal design used for CE NSSSs is such that the seal stage pressure drops are controlled by the PBD flow. The pressure drop through the PBD is calculated using the Martinelli-Nelson two-phase flow multiplier shown in Figure B2-3 extracted from Reference B2.5. This correlation provides the two-phase multiplier ($F_{2\varphi}$) as a function of pressure and mixture quality.

$$\Delta P = \frac{F_{2\varphi} \times K_{PBD} \times W^2}{288 \times g_c \times \rho_L \times (Ao)^2}$$

Where: ΔP = Two-Phase Pressure Drop (lbf/in^2)
K_{PBD} = Dimensionless Single-Phase Resistance of PBD
W = Flowrate through the PBDs (lbm/s)
ρ_L = Liquid Density (lbm/ft^3)
Ao = Tube Flow Area (ft^2)
g_c = 32.2 lbm-ft/($lbf\text{-}s^2$)
$F_{2\varphi}$ = Two Phase Multiplier

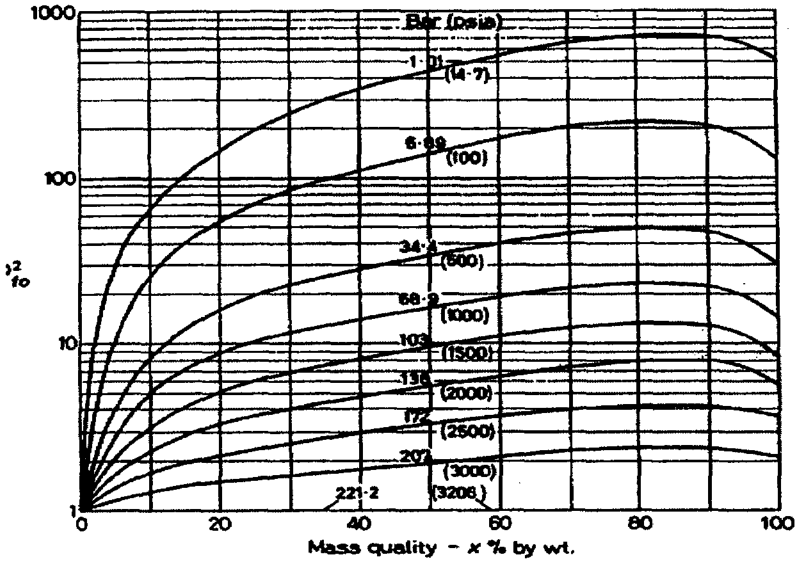


Fig. B2-3: Value of Φ_{fo}^2 as a Function of Pressure and Mass Quality (Martinelli-Nelson)

Using this methodology, revised pressure drops were calculated for the various seal stages. Since the RCS and downstream CBO discharge pressure at the volume control tank are relatively fixed, increasing the PBD resistance across saturated and nearly saturated stages will both (1) reduce the CBO flow and (2) skew the pressure distribution such that the larger pressure losses will be taken across the third stage (last PBD). A comparison of the linear single-phase distribution and the alternative distribution accounting for two-phase flow phenomena is presented in Table 2.3-1. Note that the effect of the increased resistance is to reduce the pressure drop across seal stages 1 and 2, further stabilizing both.

Table RAI 2.3-1: Typical seal stage pressure distributions

a, c

Seal Stage	RCS Pressure (psia)			
	1000	1200	1500	1800

In summary, consideration of two-phase conditions in the RCP seal indicates that while the seal pressure distribution is not linear, the two-phase behavior serves to stabilize the upstream seal stages by reducing the pressure drop of the upstream seals. Furthermore, as the risk model for both intermediate seals considered these seal stages to be subject to two-phase induced "pop-open," the details of the pressure variation does not impact the risk model.

RAI 2.4

The response to RAI 12 gives estimates of the common cause failure (CCF) Gamma factor. As the staff understands, this factor is used to address the potential that all RCPs experience a seal failure, given that one RCP experiences a seal failure. In this sense, the Gamma factor used by the Combustion Engineering Owners Group (now known as the Westinghouse Owners Group (WOG) represents a conditional probability of failure.

The WOG has identified only a few historical events that have involved multiple RCPs, of which none resulted in seal failure and only two events involved stage failures on multiple RCPs. The derivation of the Gamma factor is based on this limited data and engineering judgment with the judgment that the potential for CCF is relatively low early in the event, but will increase as the exposure time increases. The staff agrees with the basic rationale for the engineering judgment, but does not believe the resulting distribution generated by the WOG properly reflects the limited information and large uncertainties with these events. The staff believes the information presented can be used as indicators of the potential for CCF of seals by considering the information on CCF potential at the stage level (i.e., use the stage-related information as an indicator of the RCP seal CCF potential).

The staff notes that of the events involving multiple RCPs, a number of events did not experience any stage failures and reported no increased leakage. These events cannot be considered in deriving the conditional probability of multiple RCPs experiencing failures since the conditional event (failure of one RCP stage) did not occur. Of the remaining events, one event lasted only 0.1 minutes and should not be considered since its exposure time is so brief as to not expose the RCP seal stages to any significant conditions. Of the remaining events, there was either increased seal leakage or a reported stage failure. From these remaining events are the two events that involved stage failures on multiple RCPs and appear to have affected the same stage on these RCPs by the same failure mode, which is indicative of a CCF condition at the stage level. In both events, the staff understands that the affected RCPs were the only RCPs that were exposed throughout the entire event (i.e., other RCPs may have initially lost seal cooling, but cooling was restored to the other RCPs early in the event). One of these two events lasted only one-half hour and the other event lasted about 4.5 hours. The latter event is also the only event involving multiple RCPs that lasted longer than 1.5 hours. The precise timing of when increased leakage was detected, which would be indicative of when the stage failure actually occurred, is not presented. The other remaining events indicate very small leakage and/or state that only one RCP had a stage failure. Based on this limited information (i.e., a few events that exposed multiple RCPs that also involved some change in seal performance by either increased leakage or stage failure to at least one RCP, of which there are only two events that impacted the seal performance on multiple RCPs) and making a number of assumptions of when the failures occurred, the staff believes a distribution could be developed that would be technically defensible.

Please provide additional justification for the Gamma factors proposed to be used by the WOG in the RCP seal loss-of-coolant accident (LOCA) model.

RAI 2.4 Response:

Westinghouse reconsidered the information on CCF potential at the stage level (i.e., use the stage-related information as an indicator of the RCP seal CCF potential). It has been noted that of the nine events involving multiple RCPs, at least three events did not experience any stage failures and reported no increased leakage. These three events cannot be considered in deriving the conditional probability of multiple RCPs experiencing failures since the conditional event (failure of 1 RCP stage) did not occur. Of the remaining six events, one event lasted only 0.1 minutes (ANO2-1) and should not be considered since its exposure time is so brief as to not expose the RCP seal stages to any significant conditions. Of the remaining five events, there was either increased seal leakage or a reported stage failure. Two of these five events involved stage failures on multiple RCPs and appear to have affected the same stage on these RCPs by the same failure mode, which is indicative of a CCF condition at the stage level.

In both events, only the affected RCP seals were exposed throughout the entire event (i.e., other RCPs initially lost seal cooling, but cooling was restored to the other RCPs early in the event). The SL2-2 event lasted only one-half hour and the SL2-3 event lasted about 4.5 hours. The SL2-3 event is also the only event involving multiple RCPs that lasted longer than 1.5 hours. The precise timing of when increased leakage was detected, which would be indicative of when the stage failure actually occurred, is not presented. The other three events indicate very small leakage (< 3 gpm) and/or state that only one RCP had a stage failure.

This limited information shows only five events that exposed multiple RCPs and also involved some change in seal performance by either increased leakage or stage failure to at least one RCP. Of these five events, only two events impacted the seal performance on multiple RCPs. This data was used in conjunction with a number of assumption of when the failures occurred to estimate the following common cause failure probabilities:

Time	Fail Prob.	Comment

a, c

The third paragraph of Section 6.3.1 of CE NPSD-1199-P will be revised as follows:

Existing:
When all seals are exposed to the same environmental conditions, the probability of multiple RCP seal cartridge failures is established assuming the RCP failure response in each seal are independent of one another (See Section 9).

Will be changed to:

When multiple RCP seals are exposed to the same environmental conditions, the probability of multiple RCP seal cartridge failures should include a common cause factor to address the potential impact of common conditions. There is insufficient data available to calculate specific common cause factors such as β, γ, and δ. Therefore, engineering judgment is used in conjunction with the available operating experience data to estimate a common cause factor, Γ, which represents the probability that all affected RCP seals fail given that one of the affected RCP seals fails.

Table 8-1 presents the operating events involving loss of seal cooling to one or more RCPs. As shown on this table, there have been only nine events involving loss of cooling to multiple RCPs. Seven of these events involved loss of cooling to all four RCPs (ANO2-1, ANO2-1, FCS-1, FCS-3, PV3-1, SL1-2, and SL2-3), one event involved loss of cooling to three RCPs (WSES3-1) and one event involving loss of cooling to two RCPs (SL2-2). For one of the events (SL2-3) in which cooling was initially lost to all four RCPs, cooling was restored for two of the four RCPs after about 14 minutes. The time frames for which RCP seal cooling was lost in these events ranged from 0.1 hours up to 4.5 hours. None of the events resulted in a seal failure and only two of these events involved stage failures on multiple pumps. In both events involving stage failures on multiple RCPs, the information on the stage failures is limited, but they were most likely pop-open failures for stage 3.

This data is insufficient to calculate the common cause failure factors for multiple RCP seal failures given the failure of one RCP seal, but it does provide solid evidence that failure of all seals exposed to loss of seal cooling is not guaranteed given that one fails. However, as stated above, there is a potential for common cause failure of all seals exposed to a loss of seal cooling. Because of the time dependent thermal aspects of the seal failure mechanisms, the potential for common cause failure of the seals is judged to be relatively low early in the event but will increase as the exposure time increases. Using engineering judgment in conjunction with the operating experience data in Table 8-1, the following Γ factors are used to estimate the potential for common cause failure of all RCP seals affected by a loss of cooling event given that one seal fails:

[ ] a,c

These parameters were estimated based on the following considerations:

1. Common cause failure is possible but not assured.
2. The likelihood of common cause failure increases with the exposure time.
3. A Γ of [[ ]] a,c is a reasonable estimate for the 0 to 1 hour time frame because all events involving loss of seal cooling to multiple RCPs in Table 8-1 had exposure times greater than 0.1 hours and none resulted in a common cause failure of the affected seals.

RAI 2.5

The response to RAI 2 indicates that while a minimum subcooling of 20 °F is required by emergency operating procedures, plant operators routinely maintain subcooling margins in excess of 50 °F. Please describe the modified plant-specific operating procedures and the operator training program that will assure the operator actions to maintain subcooling margins in excess of 50 °F following a loss-of-component cooling water (CCW) event. Also, is the failure probability of maintaining this required operation factored into the RCP seal failure model?

RAI 2.5 Response:

Four cases that determine the RCP seal failure fault tree basic event probabilities have been examined:

(1) CBO isolated / maintain subcooling > 50°F
(2) CBO isolated / subcooling not maintained > 50°F
(3) CBO not isolated / maintain subcooling > 50°F
(4) CBO not isolated / subcooling not maintained > 50°F

These cases cover all of the plant and transient possibilities. Individual plants will need to choose the applicable cases for the plant specific PRA model. This can vary from plant to plant and transient to transient and needs to be handled appropriately.

Table RAI 2.5-1 lists where the results can be found in Reference 2.2-1 and in RAI 2.7 (due to fault tree changes). These tables include elastomer failure probability, stage pop-open failure probability and random RCP seal stage failure probability. Also included are pre-existing RCP failure, check valve failure and seal restaging due to excessive vapor stage leakage.

Table RAI 2.5-1: RCP Seal Failure Fault Tree Basic Event Probabilities

RCP Seal Failure Fault Tree Basic Event Probabilities For CBO Isolated and RCS Cold Leg Subcooling > 50°F			
Seal Design	CBO Isolated	Reference	Table
BJ/SU	Within 20 Minutes	RAI 2.7	RAI 2.7-1
BJ/SU	Within 10 Minutes	RAI 2.7	RAI 2.7-3
N-9000 / Sulzer Balanced Stator	Within 20 Minutes	RAI 2.7	RAI 2.7-5
N-9000 / Sulzer Balanced Stator	Within 10 Minutes	RAI 2.7	RAI 2.7-7
Three Stage Sulzer Balanced Stator	Within 20 Minutes	RAI 2.7	RAI 2.7-9
Three Stage Sulzer Balanced Stator	Within 10 Minutes	RAI 2.7	RAI 2.7-11
RCP Seal Failure Fault Tree Basic Event Probabilities For CBO Isolated and RCS Cold Leg Subcooling < 50°F			
Seal Design	CBO Isolated	Reference	Table
BJ/SU	Within 20 Minutes	RAI 2.7	RAI 2.7-2
BJ/SU	Within 10 Minutes	RAI 2.7	RAI 2.7-4
N-9000 / Sulzer Balanced Stator	Within 20 Minutes	RAI 2.7	RAI 2.7-6
N-9000 / Sulzer Balanced Stator	Within 10 Minutes	RAI 2.7	RAI 2.7-8
Three Stage Sulzer Balanced Stator	Within 20 Minutes	RAI 2.7	RAI 2.7-10
Three Stage Sulzer Balanced Stator	Within 10 Minutes	RAI 2.7	RAI 2.7-12
RCP Seal Failure Fault Tree Basic Event Probabilities For CBO Not Isolated and RCS Cold Leg Subcooling > 50°F			
Seal Design	CBO Isolated	Reference	Table
BJ/SU	N/A	2.2-1	9.3-1C
N-9000 / Sulzer Balanced Stator	N/A	2.2-1	9.3-2C
Three Stage Sulzer Balanced Stator	N/A	2.2-1	9.3-3C
RCP Seal Failure Fault Tree Basic Event Probabilities For CBO Not Isolated and RCS Cold Leg Subcooling < 50°F			
Seal Design	CBO Isolated	Reference	Table
BJ/SU	N/A	2.2-1	9.3-1D
N-9000 / Sulzer Balanced Stator	N/A	2.2-1	9.3-2D
Three Stage Sulzer Balanced Stator	N/A	2.2-1	9.3-3D

RAI 2.6

The response to RAI 2 indicates that the WOG analysis indicates that, without operator action, the SBO event will maintain the RCS with more than 50°F subcooling for a period of time. Please provide more discussion on the temperature transient during this event. Is a temperature transient curve available for the staff review?

RAI 2.6 Response:

The ability to control subcooling is limited for the SBO event. Analyses of SBO events have been performed for two representative CE PWRs (FCS and a typical 3410 Mwt plant) using the CE Nuclear Transient Simulation Code. CENTS is a code originally developed for use in nuclear plant simulators and is used for both best estimate and design analyses. CENTS analyses provide realistic post SBO plant responses; results of the analyses are presented in the figures below. The analyses indicate that, without operator action, the SBO event will maintain the RCS with a greater than 50°F subcooling for [[ ]] [a,c] The duration of high subcooling is a result of residual hot water in the pressurizer and the approximate 20°F hot leg-cold leg temperature difference that exists during the early natural circulation time period. Such temperature differences have been confirmed through natural circulation testing at SONGS (3410 Mwt).

In the SBO event considered above, the turbine driven AFW was considered available for the duration of the event. For situations with CBO isolated, the lower seal would lose subcooling first. However, since the seal pressure would be high at all seal stages, pop-open failures would be averted. The last or vapor seal is further protected against pop open by the lower operational temperatures, ensuring adequate subcooling. It should be noted that since it takes more than three hours for the lowest seal to reach pop-open subcooling levels and since CBO closure removes pressure drops across all seals, save the last one, CBO isolation even late in the scenario would also prevent pop-open failure.

Figure B2-4 shows the vapor stage subcooling during the BJ/SU SBO Test. This includes subcooling versus time with 50°F subcooling as a reference point.

Figure B2-5 shows the BJ/SU SBO Test Vapor Stage Seal Leakage versus time.

Figure B2-6 shows the pressurizer pressure versus time for the Fort Calhoun Station SBO with no operator action.

Figure B2-7 shows the hot leg temperature versus time for Fort Calhoun Station SBO with no operator action.

Figure B2-8 shows the subcooling for the hot and cold legs versus time for Fort Calhoun Station SBO with no operator action.

Figure B2-9 shows the RCS pressure versus time for a typical 3410 Mwt plant with no operator action.

Figure B2-10 shows the hot leg temperature versus time for a typical 3410 Mwt plant.

Figure B2-11 shows the subcooling in the hot and cold legs for a typical 3410 Mwt plant.

Figure B2-4: Vapor Stage Subcooling During BJ/SU SBO Test

a, c

Figure B2-5: BJ/SU Test: Vapor Stage Seal Leakage

Figure B2-6: FCS Station Blackout: No Operator Action: Pressurizer Pressure vs. Time

a, c

Figure B2-7: FCS Station Blackout; No Operator Action: Hot Leg Temperature vs. Time

Figure B2-8: FCS Station Blackout, No Operator Action: Hot Leg & Cold Leg Subcooling

a, c

Figure B2-9: Station Blackout: RCS Pressure: 3410 Mwt

a, c

Figure B2-10: Station Blackout: Hot Leg Temperature: 3410 Mwt

a, c

Figure B2-11: Station Blackout: Subcooling in Hot and Cold Leg: 3410 Mwt

RAI 2.7

In Figures 6.2-1, 6.2-2, 6.2-3, and 6.2-4 (of the fault trees presented in the RAI response dated April 29, 2002), there appears to be some erroneous logic, especially for cases where the vapor stage leaks enough to cause a restaging of the lower stages. Also, there is no difference in specific stage failures regardless of the CBO being isolated or not. Please confirm that the fault trees are correct or modify them to appropriately reflect the specific conditions being evaluated.

RAI 2.7 Response:

The vapor stage leakage condition is similar to the condition when the CBO is not isolated. This similarity is due to the leakage rates and temperatures being roughly the same for both the CBO not isolated case and the vapor stage leakage case. Because of this similarity, the CBO isolation case must be able to not only account for when the vapor stage does not leak, but also when the vapor stage leaks.

For the case where the CBO is isolated, the lower seal stages will, early on, be at or well below the expected equilibrium temperature (based on timing of isolation) of ~300°F. The temperatures of the lower seals will gradually increase due to conduction. Over time, the stage cavity will no longer be in saturated equilibrium, which will cause the vapor stage to reach temperatures of about 400°F. Therefore, following isolation all stages will see temperatures in the 400°F to 525°F range. See Reference B2.3, page 106, for more detail.

For the case of when the vapor seal leaks, which is similar to the CBO not isolated case, the lower seal stages will approach their equilibrium temperature in about 30 minutes with stage temperatures in the range of 525°F for the first stage down to about 500°F for the third stage. The vapor stage cavity will contain a two-phase mixture. Therefore the temperature of the fourth stage will be the saturation temperature (about 300°F) for the anticipated stage pressure of about 70 to 100 psia. See Reference B2.3, page 105, for more detail.

Given that the vapor stage leaks, the probability of elastomer failure will be lower due to lower temperature conditions on the vapor seal (as compared to CBO isolation case).

The fault tree model provided in Reference B2.3 (pages 67-88) did not correctly account for the case with CBO isolation and the vapor stage leaking. A new basic event was added for when the vapor stage leaks using the elastomer failure probabilities for when the CBO is not isolated. This is a valid assumption because the expected vapor stage leakage flowrate and temperature are roughly the same as the flowrate and temperature as when the CBO is not isolated.

Changes were made to the fault tree models in Figures 6.2-1 and Figure 6.2-3 to account for the impact on the lower temperature (as compared to the CBO isolation case) that the vapor stage is exposed to when the vapor stage leaks. The existing basic event that represents elastomer failure of the vapor stage was replaced with a basic event that reflects the difference in expected temperature of the vapor stage. The associated elastomer failure probabilities are shown in Tables 9.3-1A, 9.3-1B, 9.3-1E, 9.3-1F, 9.3-2A, 9.3-2B, 9.3-2E, 9.3-2F, 9.3.3A, 9.3-3B, 9.3-3E, and 9.3-3F. The quantified results show a small increase in the overall seal failure probability as compared to the model results presented in Reference B2.3.

Note that the difference in the specific stage failures is the change in the basic event probabilities based on CBO isolation, RCS Cold Leg Subcooling and the thermal exposure time. Each plant must choose the model that applies to the specific plant conditions based on CBO isolated/not isolated and RCS subcooling temperatures.

B.3 References

B1.1 "O-Ring Static Seal Performance Evaluation Under Loss of Component cooling Water to Reactor Coolant Pump at SONGS Units 2 and 3," Kalsi Engineering, Inc., March 1986.

B1.2 TR-ESE-754, "Test Report for the Performance Test of a Byron Jackson Pump Seal Cartridge under Simulated Plant Loss of Cooling Conditions," Combustion Engineering, Inc., June 1988.

B1.3 GS-1543, "Loss of Component Cooling Water to the Reactor Coolant Pump Seal Cartridge on Hot Standby," Byron Jackson Pump Division, November 1980.

B1.4 NUREG/CR-4821, EGG-2492, AECL-9342, "Reactor Coolant Shaft Stability During Station Blackout," Rhodes, D. B. et. Al., EG&G Idaho, Inc., May 1987 (page 7).

B1.5 CENPD-282-P-A, "Technical Manual for CENTS (Combustion Engineering Nuclear Transient Simulation) Computer Code," February 1991.

B1.6 BNL-TR W6211-08/99, "Guidance Document for Modeling of RCP Seal Failures," Ruger, C. et al, BNL, August 1999.

B1.7 GS-1520, "Loss of Component Cooling Water to the Reactor Coolant Test on Nuclear Reactor Coolant Pump," Byron Jackson Pump Division, May 1979.

B1.8 "Station Blackout Test on a Reactor Coolant Pump Mechanical Seal," Marsi, J. A., Fifth International Workshop on Main Coolant Pumps, April 21-24, 1992, Orlando, Florida.

B1.9 CEN-152, Revision 5.0, "Combustion Engineering Emergency Procedures Guidelines," Prepared for the CE Owners Group by Combustion Engineering, December 1999.

B1.10 Atwood, Corwin. L., "Hits per Trial: Basic Analysis of Binomial Date;" EGG-RAAM-11041, Prepared by Idaho National Engineering Laboratory for the Reliability and Risk Analysis Branch, Safety Programs Division, Office for Analysis and Evaluation of Operational Data, U.S. Nuclear Regulatory Commission; September 1994.

B1.11 Box, George E. P., and Tiao, George C., "Bayesian Inference in Statistical Analysis," Reading, MA; Addison-Wesley, 1973.

B2.1 Byron Jackson Report GS-1520, "Report on Loss of Component Cooling Water Test on Nuclear Reactor Coolant Pump," April 1979.

B2.2 Byron Jackson Report GS-1543, "Loss of Component Cooling Water to the Reactor Coolant Pump Seal Cartridge on Hot Standby," November 1980.

B2.3 CEOG-02-081, "Response to Request for Additional Information Concerning CEOG Topical Report CE NPSD-1199, 'RCP Seal Failure Model,' " April 30, 2002.

B2.4 Steam Tables, Properties of Saturated Steam, American Society of Mechanical Engineers, 1967.

B2.5 Collier, J.G., " Convective Boiling and Condensation," McGraw Hill, 1972, London.