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PRA Model for the Westinghouse Shut Down Seal

Westinghouse

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Executive Summary

Westinghouse has developed a reactor coolant pump (RCP) Shut Down Seal (SDS) that restricts reactor coolant system (RCS) inventory losses to very small leakage rates in the event of a plant event that results in the loss of all RCP seal cooling. The SDS is a thermally actuated, passive device that is installed between the No. 1 seal and the No. 1 seal leak-off line to provide a leak-tight seal in the event of a loss of all RCP seal cooling. The installation of the SDS will permit plants to respond to a wide range of events with only an Alternating Current (AC) independent auxiliary feedwater pump available. The possible events include station blackout, fires that disrupt power supplies, loss of component cooling system and loss of service water system. Because there would be negligible RCS inventory losses through the RCP seals, RCS makeup is no longer necessary to achieve a stable state with the reactor core being cooled.

The current Probabilistic Risk Assessment (PRA) model for RCP seal performance is the WOG2000 model that has been reviewed and approved by the U.S. Nuclear Regulatory Commission (NRC) as a "consensus" model for use in the PRA. Risk-informed applications derived from PRA studies using the WOG2000 model have become part of the fabric of plant operation and includes daily plant configuration risk management activities, Mitigating System Performance Index (MSPI) reporting, regulatory submittals for change to the plant Technical Specifications (TS), and regulatory interactions during Significance Determination Process (SDP) proceedings.

Plants installing the Westinghouse SDS will likely change their PRA to credit this enhanced safety capability. The current WOG2000 model will be supplanted by a new SDS model in the PRA. The revised PRA can then be used to modify risk-informed applications in use by the plant. In order to conserve utility and NRC resources in reviewing PRA models used for regulatory interactions, the PRA model for the SDS is being submitted to the NRC for review and approval. The actual change to the plant will require each licensee to perform a 10 CFR 50.59 assessment to determine if prior NRC approval is required for installation of the SDS.

The performance of the SDS has been verified by a large amount of testing and analysis to confirm that it meets very stringent design goals. The testing has included individual component tests as well as tests of the entire seal assembly under conditions that exceed those that are predicted for a station blackout event. The extensive testing allows the assignment of a statistically based PRA probability for the SDS failure to actuate and seal to very low leakage levels of less than 1 chance in one hundred. The testing has also shown that the likelihood of inadvertent actuation is extremely small and will not result in conditions adverse to safety.

The PRA model developed for the SDS is based on the failure modes and effects analysis (FMEA) and the subsequent testing and analysis. The statistically based failure probability for the SDS to fail to actuate and seal to very low leakage will result in a significant decrease in core damage frequency (CDF) predicted from the PRA. The actual reduction will vary from plant to plant depending on the contribution of the RCP seals to the core damage risk metric.

In addition to the reduction in the PRA risk metrics, the installation of the SDS may also permit utilities to modify their coping strategies for station blackout and fires as required by 10 CFR 50.63 and Appendix R to 10 CFR 50 respectively. By eliminating a source of RCS inventory loss, the SDS may also have beneficial effects for mitigating strategies designed to cope with security related events. It is proposed that plants installing the SDS can modify their design and/or licensing basis analyses for the RCP seal performance under a loss of all RCP seal cooling event by using an RCP seal leak rate of 1 gpm for the duration of the event.

This report also seeks NRC review and approval of that analysis model for the SDS in design and licensing basis analyses to facilitate NRC review of these revised analyses. It is recognized that plants will be required to submit revised design basis or licensing basis analyses to the NRC for plant specific approval; the NRC acceptance of the design / licensing basis Shut Down Seal performance will facilitate those reviews.

Finally, the current plant Emergency Operating Procedures (EOPs) and Abnormal Operating Procedures (AOPs) contain several steps to protect the existing RCP seals or to minimize RCS inventory losses that would no longer be necessary after the SDS is installed. The SDS eliminates concern over rapid thermal transients at the RCP seals because SDS controls leakage, not No. 1 or 2 seal; and is not sensitive to thermal shock. Also, when the SDS is actuated, RCS inventory losses through the RCP seals are minimized and therefore cooldown and depressurization of the RCS is no longer necessary to preserve RCS inventory. Thus operator response to events that result in a loss of RCP seal cooling can be enhanced by removing those procedure steps. However, the procedure steps to trip the RCPs upon a loss of RCP seal cooling remain necessary for proper functioning of the RCP seals, including the SDS. These procedure step changes will be controlled by the plant 10 CFR 50.59 assessment process to determine whether NRC review and approval is required.

Acknowledgement

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Bob Mangerie, Eric Colvin and Eric Greenawalt for expert RCP seal experience and consultation during the Shut Down Seal development and testing.

Josh Hartz, Rolv Hundal and George Konopka for engineering analyses and consultation during the Shut Down Seal development and testing.

Dr. Alan Lebeck for expert input on seal design and behavior during the development and testing of the Shut Down Seal.

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Acronyms	
AC	Alternating Current
AOP	Abnormal Operating Procedure
AOT	Allowable Outage Time
ASTM	American Society for Testing and Materials
CCW	Component Cooling Water
CDF	Core Damage Frequency
CFR	Code of Federal Regulations
Cp	Capacity Index
CRM	Configuration Risk Management
CVCS	Chemical and Volume Control System
DC	Direct Current
DI	De-Ionized
EDM	Electrical Discharge Machining
EOP	Emergency Operating Procedure
ERG	Emergency Response Guidelines
FEA	Finite Element Analysis
FME	Foreign Material Exclusion
FMEA	Failure Modes and Effects Analysis
GPM	Gallons Per Minute
ID	Inner Diameter
LOCA	Loss of Coolant Accident
LSL	Lower Specification Limit
MLE	Maximum Likelihood Estimate
MSPI	Mitigating System Performance Index
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OD	Outer Diameter
PRA	Probabilistic Risk Assessment
PSIA	Pounds Per Square Inch Absolute
PSIG	Pounds Per Square Inch Gauge
PWR	Pressurized Water Reactor
RCDT	Reactor Coolant Drain Tank
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR	Residual Heat Removal
RPM	Revolutions per Minute
SBO	Station Blackout
SDS	Shut Down Seal
SDP	Significance Determination Process
SG	Steam Generator

Acronyms	
SI	Stress Intensity
STI	Surveillance Test Interval
SW	Service Water
TB	Thermal Barrier
TBHx	Thermal Barrier Heat Exchanger
TS	Technical Specifications
USL	Upper Specification Limit
VCT	Volume Control Tank
WPS	Waste Processing System

1. INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

The Westinghouse reactor coolant pump (RCP) circulates reactor coolant fluid between the reactor core and the steam generators during normal operation to transfer heat generated in the core to the steam generators. During off-normal and accident conditions, the RCP may continue to run to provide forced circulation between the core and steam generators for enhanced decay heat removal. As long as cooling is provided to the RCP seals, the seals function normally and reactor coolant system (RCS) inventory losses are at the pre-event seal leak-off rate (nominally 3 gpm) which is within normal RCS makeup capability. Cooling to the RCP seals is provided by seal injection with thermal barrier cooling available as backup (thermal barrier only cools if seal injection fails). Operation of either means alone is sufficient to provide seal cooling.

If all seal cooling is lost, the leakage of reactor coolant through the RCP seals increases and is routed to the containment as described in WCAP-10541 (Reference 1). This results in a condition in which loss of RCS inventory can result in core uncovery if adequate reactor coolant makeup cannot be provided in a timely manner.

For plants with Westinghouse RCPs, compliance with several of the U.S. Nuclear Regulatory Commission's (NRC) regulatory requirements is impacted by the performance of the reactor coolant pump seals when all cooling is lost. Most notable of these are the station blackout (SBO) coping strategies and the fire coping strategies. The probabilistic risk assessments (PRAs) for these plants also show that the performance of the RCP seals under loss of all seal cooling conditions is a contributor to the plant core damage frequency (CDF), both for internal hazards initiating events as well as fire initiating events. A PRA model for RCP seal behavior under loss of all seal cooling conditions is provided in WCAP-15603-A (Reference 2). In many plants, the potential for the loss of all RCP seal cooling is directly tied to the performance of service water (SW) and component cooling water (CCW) since these systems provide both thermal barrier cooling as well as cooling to the charging pumps that provide RCP seal injection. The loss of all RCP seal cooling is also tied to the availability of emergency power for continued operation of the pumps providing cooling to the seals following a station blackout.

The potential for the loss of all RCP seal cooling to result in a core damage condition has been highlighted in recent applications of risk technology. In particular, the Mitigating System Performance Index (MSPI) margins for service water, component cooling water and electric power are significantly impacted at some plants by the performance of the RCP seals under loss of all seal cooling scenarios. Fire PRA considerations of loss of seal cooling and multiple spurious valve operations has also highlighted the potential for RCP seal leakage under loss of all seal cooling conditions that lead to core damage.

To provide a means for utilities to address potentially risk-significant events without the addition of alternative RCP seal cooling systems, Westinghouse has developed an RCP Shut Down Seal (SDS) that will limit RCS inventory losses to very low levels in the event of a loss of RCP seal cooling.

The information provided in this report is intended to provide a basis for a new model for RCP seal behavior under a loss of all RCP seal cooling conditions for both design and licensing basis analyses and PRA modeling. In particular, for plants installing the Westinghouse Shut Down Seal, compliance with design basis requirements would use the model provided in this report in place of the 21 gpm per RCP leakage that has previously been assumed in station blackout and fire coping strategy assessments. In addition, restoration of RCP seal cooling in these design / licensing basis analyses would no longer be restricted to prevent cold thermal shock to the RCP seals because there is no longer any cold water (e.g., cold seal injection water) passing through the RCP seal package. For utilities installing the Shut Down Seal, the model provided in this report would also replace the model described in WCAP-15603-A for PRA assessments of RCP seal performance under loss of all seal cooling conditions. Since the model in WCAP-15603-A was approved by the NRC as a consensus approach to modeling RCP seal performance in the PRA, the Shut Down Seal PRA model is also being submitted to the NRC for review and approval as a consensus PRA model.

Information provided in the Appendix to this report on the potential impacts of the revised SDS model in current PRA risk profiles and risk-informed applications are provided for information to facilitate NRC review of this report. Also included in the Appendix is a discussion of the potential procedure changes that could be made after installation of the SDS. The procedure changes would fall under the requirements for a 10 CFR 50.59 assessment to determine if prior NRC review and approval is necessary. Therefore, NRC review and approval of the information in the Appendix is not requested.

1.2 BACKGROUND

1.2.1 Reactor Coolant Pump Seals

This section provides an overview of the operation of the 3-stage seals manufactured by Westinghouse for use in RCPs. The first sub-section provides a brief overview of the design and operation of the RCP and the 3-stage seal assembly. A more complete description can be found in WCAP-10541. The second sub-section deals with seal operation under normal operating conditions. The third sub-section deals with seal operation under a loss of all RCP seal cooling scenario.

1.2.1.1 RCP Design

The RCP circulates ~100,000 gpm through the Nuclear Steam Supply System (NSSS). It takes RCS flow from the steam generator cold side outlet and pumps it to the reactor via the cold leg. A 6000 hp motor drives the pump at 1200 RPM (900 or 1500 RPM for 50 Hz designs). The motor is fitted with a substantial flywheel to ensure the continued pump rotation for a short period of time after pump trip, thus providing forced flow cooling of the reactor immediately after the pump is tripped.

The RCP hydraulic section consists of an impeller, diffuser, casing, Thermal Barrier Heat Exchanger (TBHx), lower radial bearing, main flange, and pump shaft. There are four different RCP models used in the USA as described in WCAP-10541; all are quite similar in component pieces and performance. Figure 1-1 provides a cut-away of a Model 93A RCP.

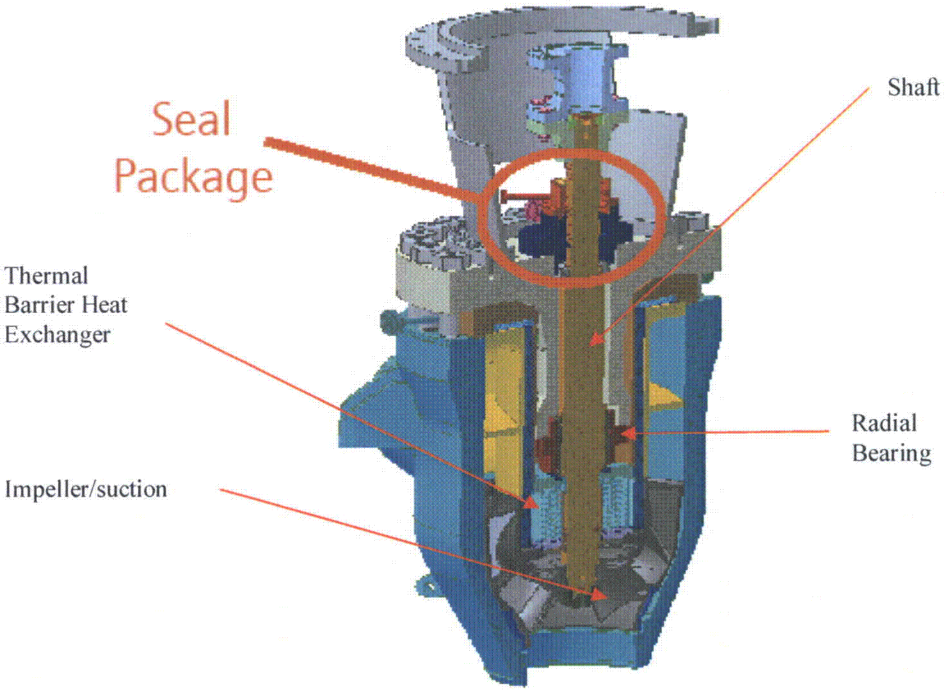
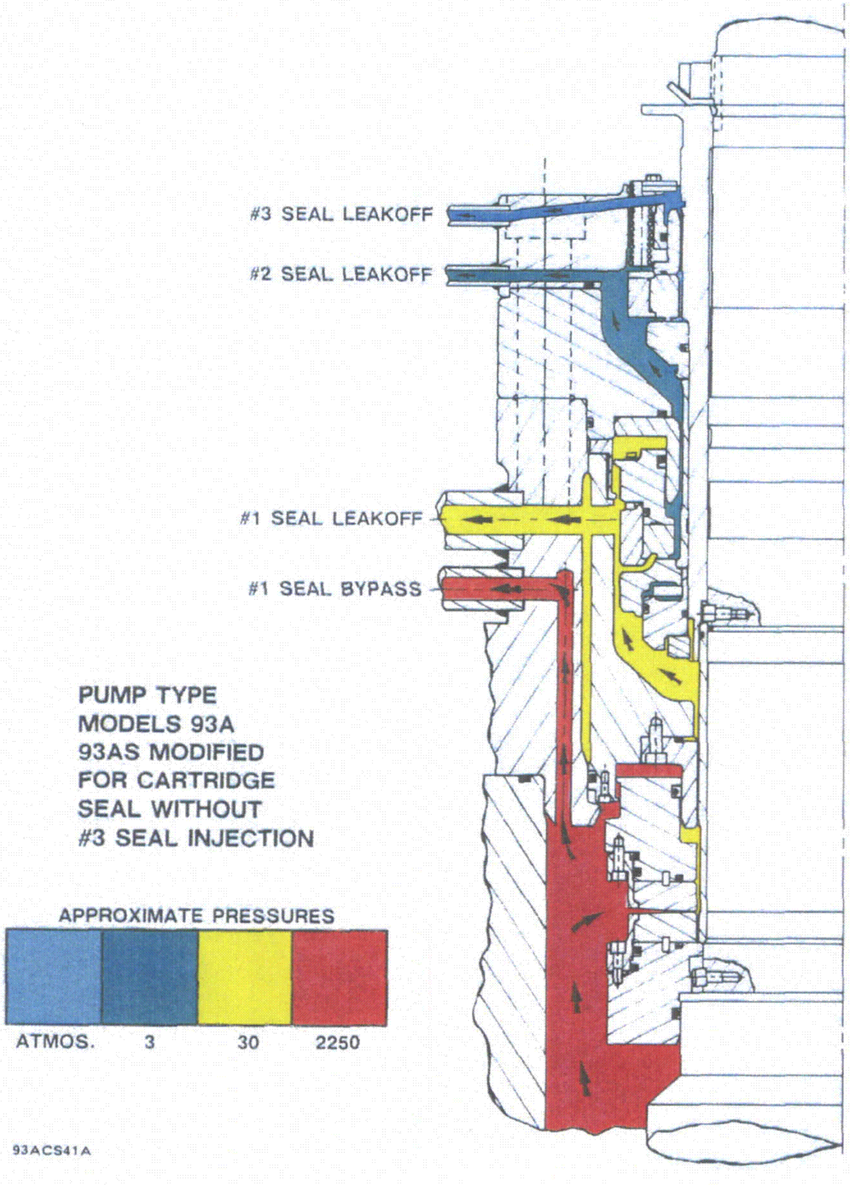


Figure 1-1 Cut-Away Of RCP Pump Showing Location Of Seal Package

1.2.2 RCP Seal Design

The seal assembly consists of three seals operating in series along the pump shaft just above the main flange. These seals reduce the RCS pressure from 2250 psia to containment ambient pressure as shown in Figure 1-2. The shaft is nominally 8 inches in diameter (7 inches for 50 Hz designs).



1.2.2.1 No. 1 RCP Seal

The No. 1 seal is the primary seal of the pump and is located above the lower radial bearing and constitutes the most important element of the seal package. It is a film-riding face seal. The film is produced by the system pressure drop across the seal and therefore does not require seal rotation. To maintain the film, a controlled leakage passes between the radially tapered seal faces. This leakage is radially inward toward the shaft. Because the seal ring (non-rotating faceplate which is attached to seal housing) rides on the film, it does not come in contact with the runner (rotating faceplate that is attached to the shaft). The seal ring can move axially to accommodate axial motions of the shaft. The seal inlet pressure is RCS pressure while the outlet pressure is nominally 30 psig. The pressure on the downstream side of the seal is controlled by the flow resistances in the No. 1 seal leak-off line and the volume control tank (VCT) pressure. The gap between the two seal faces is held at a constant distance by the design of the seals where the closing forces (which tend to close the gap between the runner and the ring) are equal to the opening forces of the fluid film during normal operating conditions. The sealing function is pressure dependent and does not change with shaft rotation (rotation is not required to establish the film of hydrostatic seals). The flow through the No. 1 seal gap, except for the small amount of No. 2 seal leakage, is returned to the VCT and the suction of the charging pumps.

1.2.2.2 No. 2 Seal

The No. 2 seal is a rubbing face seal. This seal directs the majority of the leakage from the No. 1 seal to the VCT via the No. 1 seal leak-off line. Leakage through the No. 2 seal is diverted to the Reactor Coolant Drain Tank (RCDT). In normal operation, the No. 2 seal operates with a differential pressure of approximately 30 psid across the face. The inlet pressure on the seal is normally determined by the VCT pressure and the back pressure is determined by the head of water maintained above the No. 2 seal leak-off connection and/or pressure in the RCDT. As a result of the very low leak rate through the No. 2 seal, the indicated leakage in the No. 1 seal leak-off line is representative of the total flow passing through the No. 1 seal.

1.2.2.3 No. 3 Seal

The No. 3 seal is also a rubbing face seal. This seal directs the leakage from the No.2 seal to the No. 2 seal leak-off line. The normal leakage through the No. 3 seal is measured in cubic centimeters per hour which is diverted to the radwaste system. The inlet pressure is typically 3 psig while the outlet pressure is atmospheric. There are two types of No. 3 seals in Westinghouse RCPs: a cartridge seal and a bellows seal. Both serve the same purpose although the cartridge seal is capable of withstanding significant pressure differentials compared to the bellows type seal.

1.2.2.4 Non-Rotating Seals

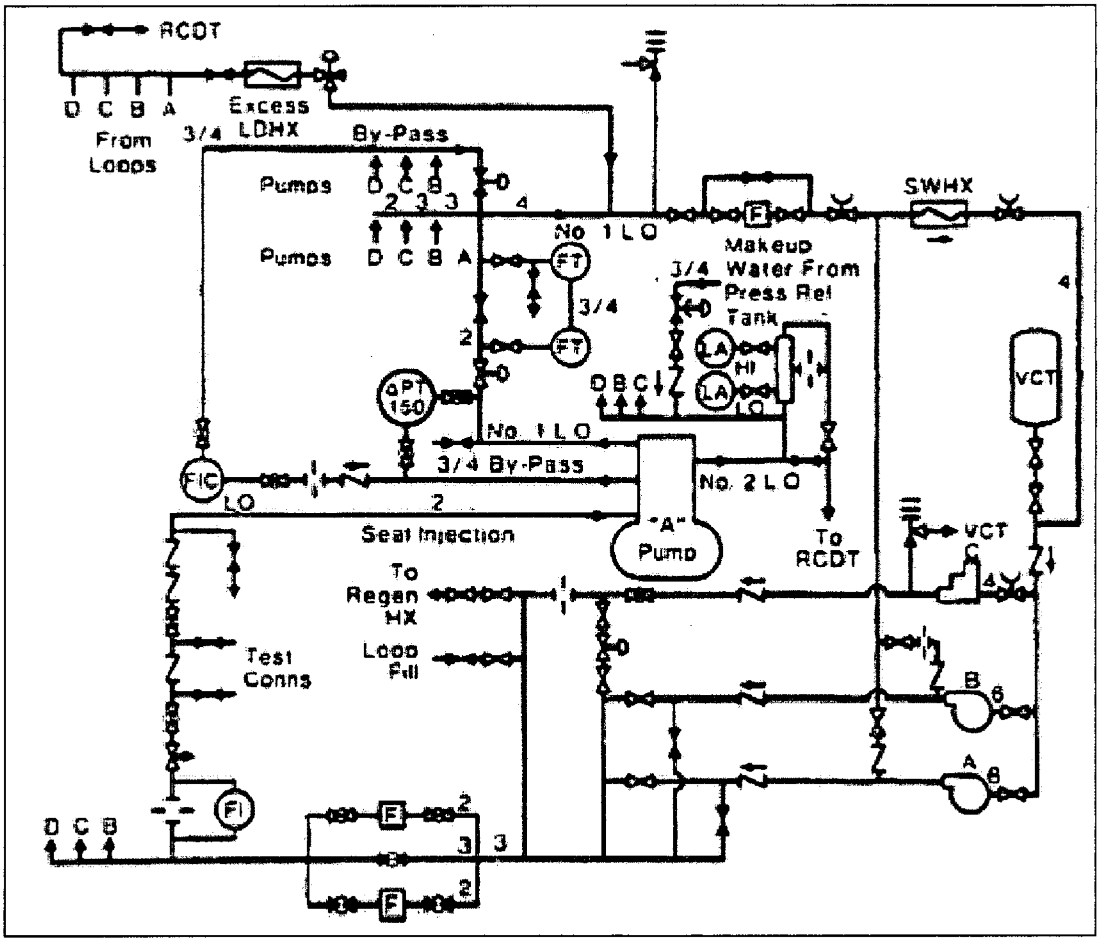
Within the seal assembly, O-rings provide sealing between components that are in static contact while a channel seal is used for locations where sliding contact occurs, between the seal rings and the seal housing inserts. The channel seal permits the ring to move axially to follow shaft motions during pump operation and maintain a constant gap in the No. 1 seal as reactor coolant system pressure and temperature change.

1.2.2.5 Seal and Radial Bearing Cooling

Cooling of pump components above the impeller is provided by the thermal barrier (TB), the TBHx and a seal water injection system. The TB and TBHx are located between the impeller and the lower radial pump bearing while the seal injection is introduced between the TB / TBHx and the lower radial bearing, or on some plants above the radial bearing.

The TB uses a set of concentric cans to limit heat transfer through the metallic pump components between the hot system water and components above the impeller. The TBHx uses CCW to cool water flowing from the RCS to the radial bearing and seal in the event of a loss of seal injection.

The seal injection flow is provided by the charging pumps and enters the pump either above or below the radial bearing, depending on pump model. Injection water at slightly higher pressure than the RCS and at a flow that exceeds the No. 1 seal leak-off rate during normal operation supplies the radial bearing and seal with cool, filtered water. The injection flow not leaking past the No. 1 seal flows down past the TB and TBHx and joins the RCS circulating flow through the discharge of the pump. This flow acts as a buffer between the hot reactor coolant and the remainder of the pump. Figure 1-3 describes the interaction of the seal flows with the Chemical and Volume Control System (CVCS) and the Waste Processing System (WPS).



Either cooling mode, on its own, is capable of maintaining the pump components, including the bearings and seals, in an acceptable temperature range to prevent damage during operation or beyond design basis accident conditions.

Each pump is equipped with two thermocouples located in the vicinity of the lower radial bearing and the No. 1 seal to provide control room indication of the water temperatures in these areas. The exact location of these thermocouples varies with pump model. The seal temperature indications are typically through the plant computer and the alarms are also computer alarms as opposed to board annunciators.

1.2.3 RCP Seal Function

1.2.3.1 Normal Operation

During normal operation, the seal injection system provides the RCP seal package with flush water which is required for optimal seal performance. The TB limits heat transfer from the hot RCS fluid to pump components above the impeller. The TBHx provides a redundant means of cooling the radial bearing and seals if seal injection is lost.

The seal injection is provided by the charging pumps that are used to maintain RCS inventory during plant operation. Seal injection is nominally at just greater than 2250 psia and recommended to be maintained near 130°F, but some plants have been known to run at seal injection temperatures as high as 190°F. The total seal injection flow to each pump is typically 8 gpm. The amount flowing up versus down the shaft depends on the specific conditions of the installed seal. Nominal flow through the No. 1 seal is 3 gpm and can vary during the life of the seal. The normal operating range is 1 to 5 gpm.

1.2.3.2 Alarms and Responses

The No. 1 leak-off flow alarm settings are 1.0 gpm and 5.0 gpm with reactor and pump shutdown specified in procedures at less than 0.8 gpm or greater than 6 gpm. If the high alarm is reached (and verified that flow is high) the behavior of the radial bearing and No. 1 leak-off temperature dictates the shut down response. If either temperature is trending higher and the unit is in Mode 1 or 2, the operator is to trip the reactor and stop the affected pump. If in Mode 3 or lower, the unit is permitted to operate with one less RCP without tripping the reactor; only the affected pump is stopped. If, on the other hand, the temperatures are stable or dropping, the operator is to initiate a controlled shut down to Mode 3 and should remove the RCP from service within 8 hours.

The high temperature alarm settings for both the No. 1 seal leak-off and lower pump bearing is between 180°F and 190°F, depending on the pump model. If the setpoint is reached, the operator is directed to shut the pump down as soon as possible (initiate controlled shut down to Mode 3 and remove affected RCP from service).

1.2.3.3 Immediate Pump Shutdown Criteria

An immediate pump shutdown is required if any of the following seal-cooling-relevant setpoints are exceeded:

- The No. 1 seal leak-off temperature exceeds high alarm setting WITH rising pump bearing or No. 1 seal leak-off temperatures,
- The No. 1 seal leak-off temperature exceeds 225°F (or alternate value in the RCP Vendor Manual),
- The pump bearing temperature exceeds 225°F (or alternate value in the RCP Vendor Manual), or
- The pump No. 1 seal leak-off rate is less than 0.8 gpm or greater than 6.0 gpm.

1.2.3.4 Response during a Loss of All Seal Cooling

A loss of all seal cooling is defined as the coincident loss of all TBHx cooling and seal injection cooling. As discussed in Westinghouse Technical Bulletin TB-04-22, Revision 1, (Reference 3), proper functioning of either TBHx cooling or seal injection will maintain the seal and bearing temperatures within the acceptable range. This prevents the No. 1 seal or bearing temperatures from reaching levels that would result in a significant change in the No. 1 seal leak-off rate.

1.2.3.4.1. No. 1 Seal Behavior

Shortly after a loss of all seal cooling, the RCP will be tripped either by operator actions or as a result of losing normal Alternating Current (AC) power as in a station blackout. The RCP will begin a coast down and typically stops in about three minutes. Since there is no seal injection, the water flow in the pump shaft annulus region is reversed and hot reactor coolant fluid begins to flow upward toward the seal package. The water passing through the No. 1 seal would initially be the clean/cool seal injection water that was in the shaft annulus above the TBHx just prior to the loss of all seal cooling.

The time between initiation of the event and the time at which the No. 1 seal is exposed to RCS fluid at cold leg temperatures depends upon the volume of clean cool water in the annulus and the No. 1 seal leak rate during normal operation. This leak rate does not change with the pump trip and coast down since the pressure and temperature of the seal environment have not changed. WCAP-10541 states that the lower internal water volume would begin to be purged within approximately 4 to 10 minutes and would be followed by an increase in seal temperature due to the in-surge of high temperature reactor coolant. The RCP seal behavior described in WCAP-15603-A, Revision 1, assumes that in 13 minutes following a loss of all seal cooling, the volume of the lower pump internals would be completely purged and the seal area water temperature would be approaching the 550°F RCS fluid temperature. A more accurate estimate for purge time can be calculated using the pump's actual purge volume and dividing that by the leak rate at the time of the event, per Technical Bulletin TB-04-22, Revision 1.

As the seal inlet fluid approaches RCS cold leg temperature, the system will go through a transient where the leakage from the seal will abruptly increase, but within several minutes will attain a steady-state flow as the pump components attain thermal equilibrium with their new environment. This flow will be greater than normal operation, but nearly half that of the transient flow. This leak rate will stabilize at 21 gpm as discussed in WCAP-10541. The reason for the higher leakage is that for a low balance ratio seal, under a phase change condition across the face, the lifting force of the two-phase fluid becomes higher than that for liquid only at the same film thickness so that the seal must open to a larger gap to have an equilibrium operating point. The new steady-state conditions differ from normal operating in the following aspects, all of which tend to increase leakage:

- Decrease in fluid viscosity due to temperature increase,
- Transition from laminar to turbulent flow due to decreased fluid density,
- Two-phase flow between seal faces resulting from flashing of hot fluid between faces,
- Thermal gradients in seal assembly components, and
- Change in pressure gradient across seal components.

1.2.3.4.2. No. 2 Seal Behavior

The No. 2 seal normally operates in a rubbing face or boundary lubricated mode. However, the No. 2 seal has been deliberately designed to enter a film-riding mode when exposed to higher differential pressures, such as the predicted 800 psid differential for a loss of all seal cooling event. The No. 2 seal achieves film-riding by using pressure induced mechanical deflections to cause convergence of the normally flat parallel faces of the No. 2 seal ring and runner. This results in an increased lifting force that causes the ring to separate from the runner. The leak rate is greater in the film-riding mode because the separation between the sealing surfaces, as well as the differential pressure across the seal face, is greater. However, a high thermal gradient across the seal faces causes a divergent seal face to develop, which results in high closing loads. Thus, the No. 2 seal is expected to roll divergent and close following a loss of all seal cooling thereby limiting the leakage through the No. 1 seal to 21 gpm by maintaining a high pressure in the chamber between the No. 1 and No. 2 seals.

The NRC, in their Safety Evaluation on WCAP-15603-A, Revision 1, postulated that the No. 2 seal could pop open before the No. 2 seal faces become divergent and thus fail to provide a significant back pressure in the chamber between the No. 1 and No. 2 seal. In this case, it is estimated that the leakage through the No. 2 seal could be as high as 182 gpm. It is noted that this phenomenon has not occurred in the operating history of the RCP seals, including a number of incidents of loss of all seal cooling as described in WCAP-16396-NP (Reference 4).

1.2.3.4.3. No. 3 Seal Behavior

The behavior of the No. 3 RCP seal only becomes important if the No. 2 seal does not remain functional during the loss of all seal cooling event. WCAP-10541 assessed the performance of the cartridge No. 3 seal, for the case of a No. 2 seal that is partially damaged or is in a film-riding mode prior to coming to thermal equilibrium. The study showed that a high thermal gradient causes a divergent seal face to develop, similar to the No. 2 seal behavior, which results in high closing loads. For this design, it was concluded that the cartridge No. 3 seal offers significant capability to limit leakage from the RCP seal package.

The performance of the bellows No. 3 seal design is not discussed in WCAP-10541. The bellows design cannot be relied upon to handle significant pressure differentials.

1.2.3.4.4. O-Ring Survivability

The non-rotating seal components described earlier (the O-rings and channel seal) are designed and tested to assure long term survivability when in contact with hot reactor coolant fluid as described in WCAP-10541. Survivability testing of the first batch of material used for the O-rings is described in WCAP-10541, Supplement 1 (Reference 5). The testing regime was comprised of exposure to accident pressure and temperature for a prolonged time period followed by increasing pressure until failure occurs. The test fixture was designed to simulate the most severe possible extrusion gap for the O-rings. The lowest failure pressure of the O-rings in this batch of material was 1710 psig. As the original batch of O-ring material was used, it became necessary for a second and, more recently, a third batch of O-ring material to be procured. Subsequent testing of these later batches of O-ring materials, using the same survivability test program that was used for the first batch, shows that the lowest failure pressure was significantly higher for the last batch. This is attributed to slight changes in the O-ring material for improved high temperature extrusion resistance.

Therefore, the 1710 psig limitation on O-ring survivability is considered to be no longer applicable since O-rings from the first batch are no longer in service.

O-rings for the SDS will all be manufactured from the latest third batch of O-ring material. However, as discussed later in this report, there are only a very limited number of O-rings that would be exposed to the high pressure differentials resulting from actuation of the SDS and in most cases, the extrusion gaps are predicted to close due to thermal expansion of the contiguous components. The one that will have an extrusion gap was tested using the process for the existing RCP O-rings. Details are found in Section 3.2.4 of this report.

1.2.3.4.5. Postulated Seal Failures

The WOG2000 PRA model in WCAP-15603-A for RCP seal behavior under a loss of all seal cooling event has four basic scenarios. In the first scenario, all of the seal stages perform as designed limiting RCS inventory loss through the seal package to 21 gpm per RCP. This was assigned a probability of occurrence of 0.79. The second scenario assumes that the No. 1 seal would "bind" in an open position in spite of the closing forces on the back side of the No. 1 seal and, assuming that the No. 2 seal closed as designed, results in an RCS inventory loss of 76 gpm per RCP. This was assigned a probability of occurrence of 0.01. The third scenario assumes that the No. 1 seal behaved as designed, but that the No. 2 seal would "pop" open and result in an RCS inventory loss of 182 gpm per pump. This was assigned a probability of occurrence of 0.1975. The fourth scenario assumes that the No. 1 seal "binds" open and the No. 2 seal "pops" open resulting in an RCS inventory loss of 480 gpm per pump. This was assigned a probability of 0.0025. The conservatisms in the WOG2000 PRA model are discussed in WCAP-16396-NP.

1.2.3.4.6. Operator Actions

The generic emergency response to the loss of all AC power instructs plant operators to use natural circulation cooldown of the RCS to cool the RCP seals following restoration of AC power if the RCP seals had been exposed to hot RCS fluid, rather than restoring seal injection or TBHx cooling. This is applicable to all plants with Westinghouse seals, regardless of O-ring material. This strategy acknowledges the uncertainty associated with the seal response to a cold thermal shock and the benefits of a decrease in RCS inventory loss as the seal leak rate decreases with decreasing RCS pressure and temperature. There is also a concern with restoration of TBHx cooling resulting in the potential loss of the CCW system integrity due to water hammer, which could result in the loss of mitigating capability for the event. The concern with restoration of seal injection was the potential for seal damage due to cold thermal shock which could increase the seal leakage rate to containment.

As described in WCAP-16396-NP, there are several instances in which seal cooling has been restored following a loss of all RCP seal cooling. In each of these instances, no damage to the RCP seals that results in high levels of RCS inventory loss have been observed. However, because the restoration of RCP seal cooling has not been fully analyzed, Westinghouse recommends in Technical bulletin TB-04-22, Revision 1, that cooling of the seals should be done by RCS natural circulation cooldown if the seal temperature exceeded the shut down limit specified in the RCP Instruction Book (typically 225°F to 235°F) rather than re-establishing seal injection. Westinghouse further recommends that following a loss of all seal cooling event, the affected RCPs be stopped immediately or at least before the seal and bearing temperatures begin to rise.

2. REGULATORY EVALUATION

The proposed PRA model for the Westinghouse Shut Down Seal that is presented below is based on the technical information provided in Section 3 of this report. Also a proposed model for deterministic analyses for plants installing the Westinghouse Shut Down Seal is presented, consistent with the technical assessments provided in Section 3 of this report. Finally, the impact of installation of the Shut Down Seal on plant procedures is presented in this section with further amplification in Section 3 of this report.

2.1 SDS DESIGN BASIS

The SDS is designed and tested to support utility compliance with various NRC requirements including 10 CFR 50.63 and 10 CFR 50.48 and Appendix R to 10 CFR 50 as well as the Probabilistic Risk Assessment (PRA) model .

10 CFR 50.63 requires a utility to identify the SBO duration it must be able to withstand and recover from, and prove its ability to do so. The duration is dependent on the redundancy and reliability of on-site emergency AC power and the expected frequency and probable time needed to restore off-site power. The coping times range from 2, 4, 8, or 16 hours. Coping times for utilities using Westinghouse RCP seals typically range from 1 to 4 hours, but for conservatism, an 8-hour coping time was considered in the development to the SDS design basis.

Appendix R to 10 CFR 50 requires that pressurizer level indication be maintained on-scale in the event of a fire in order to maintain control of the RCS pressure and thus provide a means to bring the reactor to safe shut down conditions. Appendix R also requires that the plant be able to maintain hot shut down conditions following a design basis fire and then achieve cold shut down within 72 hours.

The PRA assessments typically require a 24-hour mission time for components that mitigate the consequences of an initiating event. No core damage is assumed to occur for an accident scenario in the PRA if the plant is in a safe stable state at 24 hours after the initiating event.

2.2 PRA MODEL

The event tree shown in Section 3 was developed to illustrate the elements of successful SDS actuation to limit RCS leakage to very low levels. This detailed model was not intended to be implemented into plant specific PRA models. Rather it was intended that a very simple event tree would be implemented directly in preceding the existing RCP seal model that asks two questions:

Does the SDS effectively limit RCS inventory losses to negligible values?

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Is the reactor coolant pump tripped prior to actuation of the SDS?

For a station blackout event, the response to this question is always true because AC power is lost to the RCPs as the initiating event. For all other sequences, a human error probability needs to be determined for the operator action to trip the pump so that the SDS is actuated on a stopped or slowly rotating shaft. The cues for the operator action and the typical times available to trip the pump motors can be found in Section 3.2.3.11 of this report. As discussed earlier, alternate methods to determine a more realistic time available for RCP trip can also be used. [

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2.3 DETERMINISTIC MODEL

For plants installing the SDS, the design basis and licensing basis analyses can be changed based on a 1 gpm per pump leakage rate, consistent with the design basis requirements for the SDS. The use of 1 gpm per pump provides a large margin to the expected performance of the SDS and therefore added assurance for these types of analyses. [

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2.4 PROCEDURES

2.4.1 Emergency Operating Procedures

There are currently three limitations in the generic Westinghouse Emergency Response Guidelines (ERGs) related to the current RCP seals. The limitations are:

- Restrictions on re-establishing seal injection or thermal barrier cooling if RCP seal cooling has been lost and the temperatures exceed the criteria for RCP shut down.
- Restriction on cooling down the RCS following a loss of all seal cooling event to less than or equal to 100°F per hour to prevent thermal shock to the RCP seal package.
- The need to cooldown and depressurize the RCS following a loss of all seal cooling event to minimize RCS inventory loss through the RCP seals and therefore maximize recovery time.

Each of these limitations can remain in the generic procedures following installation of the SDS because they have no impact on the SDS performance. These limitations can be removed for RCP seal performance issues since the SDS prevents flow through the seal package when actuated and therefore the potential for RCS inventory losses and thermal shock of the seals is eliminated. However, other issues such as CCW water hammer, RCP shaft bending, bearing damage and cooldown rate limitations for other RCS components are still applicable.

The Emergency and Abnormal procedure steps to stop the RCP upon loss of all seal cooling are very important to assure the survivability of the SDS.

2.4.2 Abnormal Operating Procedures

The Abnormal Operating Procedures (AOPs) would typically provide operator guidance for fires, loss of CCW and loss of SW events that can result in a loss of RCP seal cooling. Since typical AOPs are plant specific and do not rely on a common basis similar to the ERGs, the contents may vary from plant to plant. However, the important characteristics of the AOPs can be identified as:

- Rapid diagnosis of a loss of seal cooling event followed by tripping of the reactor coolant pumps based on loss of charging pump and component cooling water flow or temperatures.
- Do not turn "on" oil lift pumps to aid in natural circulation cooling of the reactor core when all RCP seal cooling is lost.

2.4.3 Start-Up Procedures

The plant start-up procedures provide guidance on the use of the oil lift pumps during initial RCP start from cold shut down. The oil lift pumps are used to aid in starting the RCPs and are then typically turned "off" and not used again. The start-up procedures should be reviewed to confirm that the operators are instructed to turn off the oil lift pump after the RCP is started, in accordance with the RCP vendor's Instruction Manual.

3. TECHNICAL EVALUATION

3.1 SHUT DOWN SEAL DESIGN

The Shut Down Seal is a mechanical shaft sealing system which can be installed into the existing Westinghouse RCPs between the No. 1 and No. 2 seals. The SDS is passively activated based on elevated fluid temperatures on the back side of the No. 1 RCP seal. Once this seal is activated it will limit RCP shaft leakage to significantly less than 1 gpm. The SDS is a one-time use seal and must be replaced after activation.

3.1.1 Theory of Operation

The RCP Shut Down Seal is located between the No. 1 and No. 2 seals, just upstream of the No. 1 seal leak-off line as shown in Figure 3-1. The seal is located in the housing of the No. 1 Insert, encircling the shaft. The No. 1 seal Insert is modified by machining out a portion of the inner diameter at the top flange. Until activated, the seal is completely contained within the space once taken by the No. 1 Insert prior to modification. Thus the annulus between the No.1 Insert and the shaft is unaltered. The leak-off through the No. 1 seal is unimpeded on its way to the No. 1 seal leak-off line. The No. 1 seal leak-off flow is not affected during normal operation of the rotating equipment.

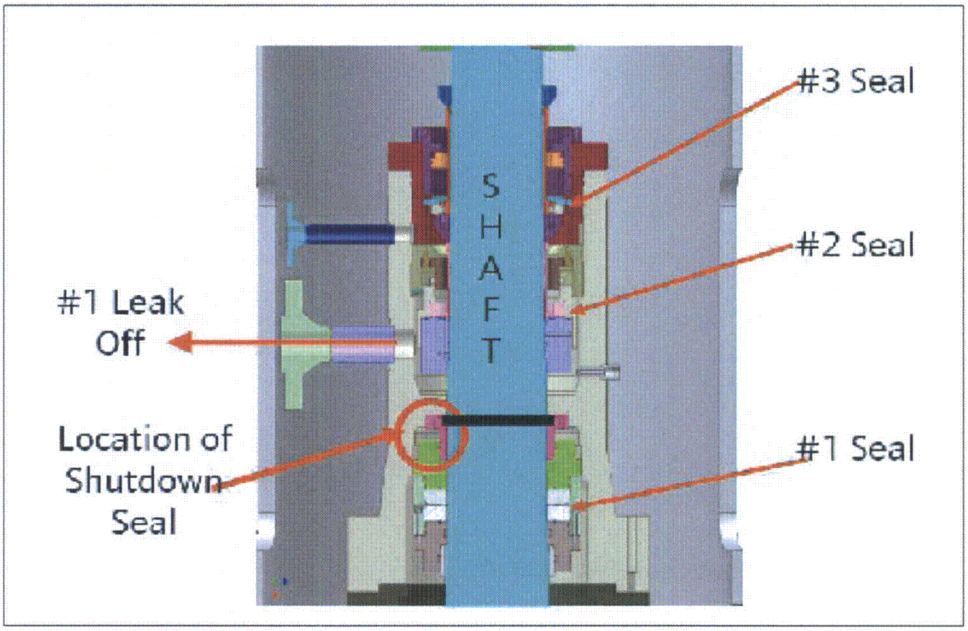

Figure 3-1 Cut-Away of RCP Seal Package With SDS

The Shut Down Seal is composed of an actuating device and a sandwich composed of a wave spring, a piston ring, a polymer ring and a retaining ring as shown in Figure 3-2. The actuating device holds the piston ring "open" permitting No. 1 seal leak-off to flow up the shaft to the No. 1 seal leak-off line. The polymer ring is sandwiched between the piston ring and the retaining ring. The retaining ring is shrink fitted and retains all of the SDS components. When assembled in the pump, the retaining ring is further retained in place by the RCP seal housing located directly above it. The wave ring is designed to maintain contact between the three rings.

When the fluid coming through the No.1 seal increases to the temperature that causes the actuator to retract the spacer from the piston ring, the piston ring snaps closed against the shaft, providing a significant flow restriction and causing the pressure to build on the back side of the polymer ring. With the flow severely restricted, the pressure at the piston ring approaches the reactor coolant system pressure which forces the polymer ring against the shaft creating a leak-tight seal.

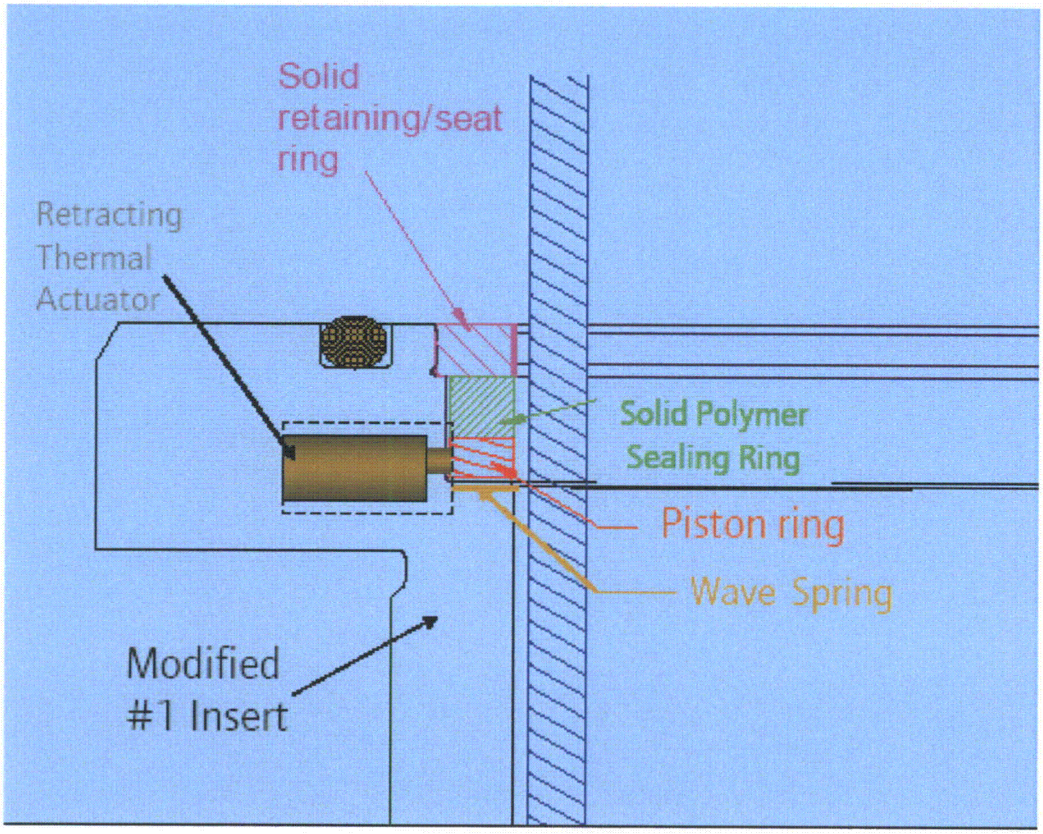

Figure 3-2 Cut-Away of Shut Down Seal

3.1.1.1 Activation and Sealing Process

The activating portion of the seal is made up of a retractable spacer holding the ends of a piston ring open. The retractable spacer is activated by a thermally responsive piston device.

While the piston ring provides a substantial flow restriction, the primary sealing ring is a polymer material that, when acted upon by the very high pressure drop induced by the piston ring interrupting the flow through the annulus, is constricted around the shaft and upwards against a retaining ring. As the primary sealing ring constricts, it creates greater pressure drop which in turn further constricts the ring tighter around the shaft and upwards. This pressure drop also forces the piston ring and retaining ring upwards, ensuring a tight seal between all the sealing surfaces. The polymer ring can conform to pump shaft out-of-roundness, scratches, dents, debris, roughness, and other surface anomalies. An advantage of the polymer is its ability to slip along the shaft axially and shift with it radially and still maintain a tight seal. This is because it is a continuous ring with a low coefficient of friction. Note the piston ring, once it initiates sealing, is no longer required for the polymer ring to seal.

3.1.1.2 Primary Sealing Ring

Using the polymer yields a leak-tight seal at RCS pressures and temperatures. [

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3.1.1.3 Retracting Thermal Actuator

The axis of the retracting thermal actuator is perpendicularly located relative to that of the shaft and is recessed into the housing of the No. 1 Insert. It is located in a bore made in the flange of the No. 1 Insert where the inner diameter (ID) has been enlarged for the sealing rings. The retracting actuator is a spring-loaded spacer restrained by a thermal piston. [

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3.1.1.4 Piston Ring

On the majority of Westinghouse RCPs in the U.S. (Model 93A), the shaft adjacent to the insert has a sleeve used as a spacer (No. 1 Runner Retaining Sleeve). The SDS will be sealing on this sleeve rather than the shaft. The piston ring for this pump model can be a [

] a,c In the other RCP models (93, 93A-1, and 100), there is no sleeve. The SDS will seal directly on the shaft. [

] a,c

The term shaft will be used henceforth to describe the cylindrical surface on which the SDS seals, but in most cases the actual surface will be a sleeve.

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] a,c

3.1.1.5 Wave Spring

The wave spring is located between the Modified No. 1 insert and the piston ring. Its purpose is to provide a slight pressure on the piston ring and polymer ring to prevent movement during normal plant operation. [

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3.1.1.6 Retaining Ring

The retaining ring is coated and lapped to a fine finish to minimize friction between it and the polymer ring to tolerate a short period of shaft coast down rotation. [

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3.1.1.7 Modified No. 1 Insert

The advantage of modifying the No. 1 Insert for the Shut Down Seal housing is two-fold. One is that this is a replacement part, so retrofitting a pump with this seal only requires replacing the existing Insert with a modified one. Secondly, modifying the Insert can be done before opening the pump for access. Installation of the modified Insert, with the SDS already installed prior to shipment to the plant in order to minimize the potential for installation damage, is the same as a non-modified one; so installation procedural changes are minimal.

3.1.1.8 Secondary Sealing Surfaces

The addition of the SDS to the Westinghouse RCP seal package necessitated a review of the secondary sealing components (O-rings), to determine any impact to the current reliability and qualification.

The Westinghouse High Temperature O-rings are qualified for service in loss of seal cooling scenarios. The original qualification was completed in the late 1980's and is documented in Supplement 1 to WCAP-10541 (Reference 5). This original qualification became the basis for the Westinghouse test specification that has been used for qualification of production master batches and qualification of any new compound formulations.

During normal operation the addition of the SDS does not affect the current qualification criteria for the secondary seals. [

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3.1.2 SDS Design Basis

The SDS is designed and tested to support utility compliance with various NRC requirements including 10 CFR 50.63 and 10 CFR 50.48 and Appendix R to 10 CFR 50.

10 CFR 50.63 requires a utility to identify the SBO duration it must be able to withstand and recover from, and prove its ability to do so. The duration is dependent on the redundancy and reliability of on-site emergency AC power and the expected frequency and probable time needed to restore off-site power. The coping times range from 2, 4, 8, or 16 hours. Coping times for utilities using Westinghouse RCP seals typically range from 1 to 4 hours, but for conservatism, an 8-hour coping time was considered in the development to the SDS design basis.

Appendix R to 10 CFR 50 requires that pressurizer level indication be maintained on-scale in the event of a fire in order to maintain control of the RCS pressure and thus provide a safe means to bring the reactor to safe shut down conditions. Appendix R also requires that the plant be able to maintain hot shut down conditions following a design basis fire and then achieve cold shut down within 72 hours.

For consideration of coping strategies for extensive plant damage events (e.g., 10 CFR 50.54(hh)) from beyond design basis causes, no time frame is provided for the effectiveness of the coping strategies.

The PRA assessments typically require a 24-hour mission time for components that mitigate the consequences of an initiating event. No core damage is assumed to occur for an accident scenario in the PRA if the plant is in a safe stable state at 24 hours after the initiating event. The 24 hours is based on an assumption that other measures can be implemented if a subsequent failure should occur.

3.1.2.1 SDS Leakage Rate Design Basis

For a fire scenario that interrupts RCS makeup and also results in a loss of all RCP seal cooling, a long term RCP inventory loss rate of less than 1 gpm per pump provides over 2 hours for recovery of RCS makeup before pressurizer level indication is lost. Further, this low level of RCP seal leakage ensures that most RCS makeup sources can be effective in maintaining pressurizer level and transitioning to cold shut down within 72 hours.

For a station blackout scenario, an RCP leakage rate of less than 1 gpm provides considerable margin to core uncovery for an 8-hour coping time.

For consideration of coping strategies for fire protection, an RCP inventory loss rate of less than 1 gpm through the SDS provides over 10 hours in which to recover a source of RCS makeup.

For extensive plant damage events from beyond design basis causes, an RCP inventory loss rate of less than 1 gpm through the SDS provides over 72 hours in which to recover a source of RCS makeup.

For the PRA, an RCS inventory loss rate of less than 1 gpm through the RCP seals provides considerably more than 24 hours in which to recover a source of RCS makeup.

These considerations assume that steam generator cooling is maintained to prevent RCS pressurization to the point where RCS inventory loss occurs through the pressurizer relief or safety valves. It is also noteworthy that RCS depressurization using the steam generators is not required in the first eight hours for either of the design bases and is not required in the first 24 hours for the PRA consideration.

Thus, an SDS design basis leakage rate of less than 1 gpm per RCP seal provides significant additional protection for scenarios involving a loss of all RCP seal cooling. A more restrictive design basis leakage rate (less than 1 gpm) does not result in a substantial additional increase in safety as measured by these considerations.

3.1.2.2 SDS Temperature and Pressure Design Basis

The SDS is designed to limit RCS inventory losses for plant events that involve a loss of all RCP seal cooling and decay heat is being removed by the steam generators. Without heat removal by the steam generators, the RCS would pressurize to the opening setpoint for the pressurizer relief / safety valves and rapid inventory loses would occur through the relief / safety valve. The Shut Down Seal would be of little value for these cases where RCS inventory is being lost through the pressurizer relief / safety valves. For cases with the steam generators removing decay heat via natural circulation, the RCS cold leg temperatures are expected to be in the range of 550°F as predicted by computerized simulations (Reference 1). [

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3.1.2.3 Duration

The longest coping time in the regulatory basis for the SDS is the 72-hour value from Appendix R to 10 CFR 50. The SDS is designed to remain leak-tight for this 72-hour time period which includes 24 hours at post-station blackout RCS system pressure and temperature followed by a rapid cooldown to normal RHR cooling (shutdown cooling) and maintaining RHR cooling conditions to 72 hours.

As described above the 8-hour and 24-hour mission times for Station Blackout coping strategies and for PRA modeling fall within the fire protection 72-hour mission time value.

3.1.2.4 Pump Shaft Rotation

The SDS is designed to operate with the shaft rotation stopped. The first indication of a loss of all seal cooling would be annunciated alarms for loss of seal injection flow, loss of CCW flow and high CCW temperatures. An alarm for high leak-off temperature would be received later and is in the range of 180°F to 190°F which also alerts the operators to a potential loss of seal cooling. At 225°F to 235°F, the RCP instruction manual calls for tripping the reactor coolant pump motor. Upon tripping the reactor coolant pump motor, the pump will coast down and, based on operating experience discussed in a later section of this report, the shaft rotation is expected to stop approximately 200 seconds after trip. To accommodate possible slow shaft rotation after pump trip, the surface of the retaining ring is polished and chrome-plated to permit the polymer ring to grip the pump shaft but still slowly rotate against the retaining ring (piston ring also grips the shaft and rotates with the polymer ring).

3.1.2.5 Response Time

The response time for the SDS should be within the time frame for transition from normal No. 1 seal leak-off to increased leakage due to the loss of all seal cooling as discussed in a later section of this report. If the SDS is activated within this time frame, it will be activated against a single-phase flow of water that is passing through the No. 1 seal and will limit RCS inventory losses to very low levels. Activation at later times could result in non-negligible RCS inventory losses before the leak-tight sealing is established. Therefore, the SDS design basis response time is taken to be a time before significant increases in leakage through the No. 1 seal would occur.

3.1.2.6 Reliability

The reliability requirements for the SDS are based on assuring that the failure to activate and limit leakage is not a dominant failure mode in the PRA and that the reliability is maximized for risk-informed applications such as MSPI. The ability of the SDS to meet the reliability goals has been demonstrated through testing and analysis of the SDS. The reliability goals include:

- Very low potential for inadvertent actuation during normal operation to ensure that the initiating event frequency for inadvertent actuation does not contribute to the PRA initiating event frequencies, as well as for plant asset management considerations.
- Passive activation at a No. 1 seal leak-off temperature of 250°F to 290°F to ensure sufficient time for the operators to trip the RCP motors using existing procedures and guidance and to ensure that significant RCS inventory loss through the RCP seals does not occur prior to activation of the SDS.
- Less than 1 gpm leakage following activation to eliminate the need for immediate manual operator actions to restore RCS makeup for Appendix R fire scenarios and station blackout scenarios.

The target level of reliability for the Shut Down Seal that is demonstrated through testing and analysis is: [

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3.1.2.7 Service Life

Currently the service life-limiting component in the RCP seal package is the high-temperature O-ring. Currently its service life is qualified for 6 years. However, an investigation is underway to extend that qualification to 9 years. The SDS will meet or exceed this new life limitation.

3.1.2.8 Material Selection

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3.2 SDS PERFORMANCE ASSESSMENTS

This section describes the failure modes and effects analysis that guided the SDS analysis and testing to demonstrate the target levels of reliability.

The test equipment as well as the test results are also presented in this section. A guide to the test machines and the test results is provided in Table 3-1. Note that for instances where testing is still in progress, the information will be provided in an update or addendum to this report when testing is complete.

Table 3-1 Guide to Test Machines and Test Results

3.2.1 Failure Modes and Effects Analysis

A Failure Modes and Effects Analysis (FMEA) was performed on the SDS as detailed in Table 3-2. This was used as a basis for the test plans and design requirements. This form of analysis systematically identifies all possible scenarios in which a design will be expected to perform (shown as "Product Function" in table). For each scenario the analysis identifies the potential ways that the design can fail to meet the design intent (shown as "Potential Failure Mode" in table). For every mode of failure, its impacts are assessed ("Potential Failure Effects"). Then the existing controls and procedures (fail-safe, tests, calculations) that prevent either the cause or failure mode is identified in the column "Current Process Controls." Those with the greatest risks have follow-up actions identified as listed in "Future Controls."

Each mode or effect in the FMEA is addressed in detail in this report.

Table 3-2 Failure Modes and Effects Analysis Summary					
Product Function	Potential Failure Mode	Potential Failure Effects	Potential Causes	Current Process Controls	Future Controls

a,b,c

Table 3-2 Failure Modes and Effects Analysis Summary

Product Function	Potential Failure Mode	Potential Failure Effects	Potential Causes	Current Process Controls	Future Controls

a,b,c

Table 3-2 Failure Modes and Effects Analysis Summary

Product Function	Potential Failure Mode	Potential Failure Effects	Potential Causes	Current Process Controls	Future Controls

a,b,c

Table 3-2 Failure Modes and Effects Analysis Summary

Product Function	Potential Failure Mode	Potential Failure Effects	Potential Causes	Current Process Controls	Future Controls

a,b,c

Table 3-2 Failure Modes and Effects Analysis Summary

Product Function	Potential Failure Mode	Potential Failure Effects	Potential Causes	Current Process Controls	Future Controls

a,b,c

3.2.2 Test Equipment

For research purposes, as well as to test prototype components and qualify the final SDS product, Westinghouse has built a series of testing machines and mock-ups specifically for this project. This section describes in detail these machines, their operation, and test capabilities. There are certain design details which must be understood in order to correctly interpret the test results and special emphasis is placed on these details.

3.2.2.1 Static Testing Machine

The static tester, shown in Figure 3-3, has been designed and built to duplicate the mechanical interface between the SDS as installed in the No. 1 Insert and the RCP seal housing. [

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a,b,c

Figure 3-3 Westinghouse Shut Down Seal Static Testing Machine

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3.2.2.1.1. Shut Down Seal Leak Test in Static Testing Machine

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3.2.2.1.2. Axial Movement Using the Static Testing Machine

The purpose of axial testing is to determine the ability of the SDS to work correctly as the axial relationship between the seal and shaft slowly change as a result of asymmetric heating caused by the entrance of water at RCS temperatures. [

] ^{a,b,c}

3.2.2.1.3. Lateral Displacement Using the Static Testing Machine

The same thermal issues that may cause an axial displacement of the sealing surface relative to the SDS may also cause lateral displacements. This could result from bending of the RCP shaft caused by asymmetric heating. [

] a,b,c

3.2.2.1.4. Sealing Surface Flaw Testing in the Static Tester

To confirm that the SDS will function as designed against potentially defective surfaces, a test program was undertaken in which the SDS leak rate performance was measured when sealing against known defects.

The sealing surface for the SDS in the Model 93A RCPs consists of a replaceable sleeve. The SDS will be furnished with a new sleeve whose diameter and surface finish will be precisely controlled. For all other models of pumps, sealing must occur directly against the RCP shaft. Since these pumps have been in service for many years, and have undergone numerous maintenance cycles, the sealing diameter may have some flaws and blemishes. These may have occurred as a result of tools striking the surface or they may have existed since manufacture. Prior to the SDS, these diameters were not critical surfaces and larger manufacturing tolerances were applied both to diameter and surface finish.

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3.2.2.2 Dynamic Testing Machine

The dynamic test machine accepts RCP No. 1 faceplates and can perform a full range of pressure and flow tests from 230 psig to 2500 psig both statically and at 1200 RPM. [

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a,b,c

Figure 3-4 RCP Dynamic Test Machine

3.2.2.2.1. Rotation Torque Testing

A basic assumption in the design of the SDS is that the RCP will have come to a complete stop prior to, or shortly after, actuation and will remain stopped during the course of the accident. However testing was performed to determine how the seal would perform, and survive, if it inadvertently were exposed to rotation.

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3.2.2.2.2. Low Speed Testing

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3.2.2.2.3. Full Speed Testing

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]^{a,b,c}

3.2.2.3 Actuator Piston Testing Machine

[

]^{a,b,c}

a,b,c

Figure 3-5 Westinghouse Actuator Piston Testing Machine

[

] a,b,c

3.2.2.4 Crud Tester

An important consideration in the SDS design is the SDS endurance and corrosion resistance. A crud test machine was developed as shown in Figure 3-6. [

] a,b,c

a,b,c

Figure 3-6 Westinghouse Dynamic Crud Testing Machine

3.2.3 Test Results

3.2.3.1 Sealing Endurance Tests

The most challenging requirement the SDS must meet is the endurance test. Withstanding 570°F and 2350 psia for 24 hours leaking less than 1 gpm must be demonstrated to meet the design specification. [

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3.2.3.1.1. Test Results

Using the static testing machine, the SDS seal was tested repeatedly at full pressure and various temperatures. [

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Table 3-3 Table of Tests on SDS in Static Test Machine

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Figure 3-7 Plot of Key Variables for 29-Hour Endurance Test with T > 550°F

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3.2.3.1.2. Statistical Analysis

3.2.3.1.2.1. Failure to Seal to Design Criteria

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] a,b,c

3.2.3.1.2.2. Failure to Remain Sealed for Event Duration

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Table 3-4 Hour-Interval Leakage from Shut Down Seal

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Table 3-5 Cumulative Leakage from SDS for Each Hour Interval

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[

] a,b,c

3.2.3.1.2.3. Weibull Analysis

The fact that none of the tests have ever failed makes it difficult to predict the life of the SDS. Note, no tested seal upon inspection ever showed any indication it was even remotely approaching failure. On the contrary, the seals showed no sign of deteriorating over time. That is further discussed in the next section.

A statistical analysis was performed on the data to draw conclusions about the expected life of the SDS under loss of seal cooling. The Weibull distribution is widely used in reliability and product life data analysis. In fact life data analysis is often called "Weibull analysis" because the Weibull distribution is the most popular distribution for analyzing life data.

The advantage of the Weibull distribution is its versatility; it can mimic the behavior of other statistical distributions including the exponential, log normal, and the well known normal distributions. Statistical software is used to derive a life distribution function that most closely fits the data, without previous knowledge of the product or its failure modes (i.e., whether it is normal, etc.). The derivation of the distribution is based on the data and goodness of fit tests. In this case, the data was not actually failure data because the SDS never failed. This is referred to as "censored" data; specifically right-censored which is defined as the time after which the failure occurred. The Maximum Likelihood Estimate (MLE) must be used in such cases. MLEs are calculated by maximizing the likelihood function. This function describes, for each set of distribution parameters, the chance that the true distribution has the parameters based on the sample (test data). With no historical values to use as distribution parameters (not specific to the SDS, that is), a Bayes analysis is used to obtain the lower confidence bounds for parameters. Without a single failure the likelihood function is unbounded and the usual MLE method breaks down. A conservative approach to address this is to introduce a failure, by treating a right-censored data point as though it were a failure. Ideally, the one data point chosen to be a failure should not be the longest successful test, but rather the second longest. This is extremely conservative.

[

] a,b,c

Table 3-6 Table of Survivabilities for SDS from Weibull Analysis

a,b,c

[

] a,b,c

3.2.3.2 Polymer Ring Extrusion

As described previously, the polymer ring is held in place between the metal piston ring and the metal retaining ring. When the SDS is actuated, the piston ring closes against the pump shaft to create a high pressure area behind the polymer ring which causes the polymer to flow in against the shaft providing a leak-tight seal. Since the retaining ring does not move and a small gap remains between the retaining ring and the shaft, the polymer ring can flow into this gap since the high pressure is maintained on the back of the polymer ring until RCS pressure is decreased.

[

] a,b,c

Table 3-7 Polymer Ring Extrusion after High Temperature Testing

a,b,c

[

] a,b,c

Table 3-8 Regression Analysis of Polymer Extrusion Data

a,b,c

a,b,c

Figure 3-8 Regression Analysis Results for Polymer Extrusion

[

] ^{a,b,c}

3.2.3.3 Actuation Testing

Several series of actuation tests have been completed to assure the reliable actuation of the SDS as described below.

3.2.3.3.1. Retracting Tests

[

]^{a,b,c}

<table>
<tr><th colspan="6">Table 3-9 Maximum Force Data for Thermal Actuator Pistons</th></tr>
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3.2.3.4 Seal Assembly Actuation

A series of tests were performed in the static tester with complete SDS assemblies to verify the reliability of activation to initiate sealing. [

] a,b,c

<table>
<tr><th colspan="6">Table 3-10 Actuation Tests of SDS Assembly in the Static Tester</th></tr>
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</table>

a,b,c

The results of these tests show no failures [

] a,b,c

3.2.3.5 Oven Testing

After having proven that the whole SDS assembly reliably retracts and seals in the static tester, simple oven tests were performed to increase the statistical confidence interval predicting the reliability of the retracting actuator to retract the spacer from between the piston ring ends. [

] a,b,c

a,b,c

Table 3-11 Actuation Temperature for Non-Irradiated Samples

[

] a,b,c

3.2.3.6 Radiation Testing

[

] ^{a,b,c} The purpose of the radiation test program was to determine if exposure to the radiation expected over the seal lifetime would impact the performance [

] ^{a,b,c}

The total lifetime dose of 200,000 rads was determined by reference to previous testing of elastomeric components used in the RCP No. 1 seal. This evaluation was previously done by Westinghouse and is documented in WCAP-10541. The evaluation concluded that a total dose of 150,000 rads would result from an exposure to a typical seal component lifetime of 54 months (4.5 years). For the actuator testing program, the dose was increased to 200,000 rads to match the current RCP seal lifetime of 72 months (6 years) and later to 350,000 rads for an extended 9-year RCP seal life that is currently being investigated.

[

]^{a,b,c}

a,b,c

Figure 3-9 Example Effect of Radiation on Actuation Temperature

Table 3-12 Piston Extension Testing For Irradiated Samples

a,b,c

Table 3-13 Piston Extension Testing For Control Samples

a,b,c

[

]^{a,b,c}

In comparing the radiated samples with the non-radiated control, linear regression shows that radiation has no effect [

]^{a,b,c}

3.2.3.7 Actuator Temperature Testing

[

] ^{a,b,c}

a,b,c

Figure 3-10 Process Capability Analysis of Thermal Actuator

[

] ^{a,b,c}

[

]^{a,b,c}

3.2.3.8 Thermal Piston Soak at Pressure Testing

A sample of 10 thermal pistons has been exposed to de-ionized (DI) water at 140°F and 25 psig in the Westinghouse Crud Tester. Another sample of 10 thermal pistons has been exposed to mid-cycle RCS water with concentrations of boric acid and lithium hydroxide (1250 ppm boron as boric acid, 2.5 ppm lithium as LiOH) at 190°F and 35 psig circulating in an autoclave. The crud tester shaft rotated at 1200 RPM to simulate the effect of an actual RCP seal package. [

]^{a,b,c}

3.2.3.8.1. 140°F Thermal Piston Soak at Pressure Testing

The results obtained to date for the 140°F soak test are presented in Table 3-14. [

]^{a,b,c}

Table 3-14 140 Degree Thermal Piston Soak

a,b,c

[

]^{a,b,c}

3.2.3.8.2. 190°F Thermal Piston Soak at Pressure Testing

The results obtained to date for the 190°F soak test are presented in Table 3-15. [

]^{a,b,c}

Table 3-15 Thermal Piston Soak Test at 190°F

a,b,c

Comparing the results from the 500 hours of soaking to the 1000 hours, one can see in the table above that there is virtually no change [

]^{a,b,c}

3.2.3.9 Axial Movement Tests

The purpose of axial testing is to determine the ability of the SDS to seal properly as the axial relationship between the seal and shaft slowly change as a result of asymmetric heating caused by the entrance of water at RCS temperatures.

[

] a,b,c

3.2.3.10 Lateral Movement Tests

The same thermal issues that may cause an axial displacement of the sealing surface relative to the SDS may also cause lateral displacements. This could result from bending of the RCP shaft caused by asymmetric heating.

[

] a,b,c

3.2.3.11 Shaft Rotation

The SDS is designed to deploy on a non-rotating shaft. For the station blackout event the RCPs will automatically trip on loss of AC power and the shaft will have stopped rotating by the time the SDS activates. For all other total loss of RCP seal cooling events, the operator is required to trip the RCPs to achieve a non-rotating shaft condition when the SDS is passively actuated. There are three unique situations that can result in the SDS deploying on a rotating shaft: 1) the shaft is slowly rotating such as during the RCP coast down caused by a delay in tripping the RCPs, 2) the shaft rotating at full speed due a failure to trip the RCPs following a loss of all seal cooling event, and 3) the shaft is rotating at full speed due to inadvertent actuation of the SDS (i.e., no loss of seal cooling).

Testing and analysis were performed to assess the consequences of the actuation of the SDS on a rotating shaft, both at full speed (1200 RPM) and coast down speeds (20-50 RPM).

Considerations for the design of the SDS include a stopped or slowly rotating pump shaft. This presents the need to understand the volume of water present in the seal package and the minimum time for the RCS water to purge this volume of water and begin passing through the No. 1 seal. Additionally, the time required for the RCP motor to come to a stop (coast down time) is needed. With the two values, the allowable operator response time to trip the pump motor can be determined.

3.2.3.11.1. Seal Package Purge Time

The total volume of water that has to be purged out of the pump area between the impeller and the seal package before the RCS water comes in contact with the seal package assuming a "solid slug" flow model is defined as the buffer volume. This does not consider the mixing effect of the hot RCS within the pump region before the seal package. Another volume, called the purge volume is defined to account for the mixing effect of the hot RCS with the pump; the purge volume used to calculate the time for hot RCS water to contact the seal package is conservative. These volumes vary by pump model and can vary within a pump model. A typical purge volume and buffer volume for the various RCP models are given in Table 3-16.

a,b,c

Table 3-16 Typical Purge and Buffer Volumes for Westinghouse RCP Models

The time for the RCS water to contact the seal package is a direct function of the purge volume and the seal leak rate. Dividing the purge volume by the maximum seal leak rate for the operating RCPs at initiation of the event is the Westinghouse recommended method in TB-04-22, Revision 1, to estimate the minimum time for restoration of cooling of the seals. The maximum leak-off rate recommended by Westinghouse (Reactor Coolant Pump Instruction Manual) is 5 gpm. The normal seal leak-off rate for plants throughout the fuel cycle, based on many years of operating experience, is between 2 and 3 gpm. Therefore, the time for activation of the SDS after a loss of all seal cooling can be conservatively estimated. This is conservative because it neglects the affects of the heat capacity of the thermal barrier heat exchanger and the natural circulation of CCW fluid after the loss of forced CCW cooling. The typical expected and minimum times are provided in Table 3-16. Each utility implementing the RCP SDS is expected to perform plant specific calculations for the time to SDS activation; alternate more detailed methods to that described in TB-04-22, Revision 1, may be used at the discretion of the utility.

[

] a,b,c

3.2.3.11.2. Coast Down Time

The coast down time is defined as the amount of time required for an RCP to come to a complete stop after the pump is tripped. Since the SDS contacts the shaft when activated, it is important to determine whether the shaft comes to a complete stop prior to the activation of the SDS. To determine the coast down time, both operating experience and engineering modeling were pursued.

[

] a,b,c

Table 3-17 Engineering Model for RCP Torque for Station Blackout

a,b,c

[

]^{a,b,c}

Table 3-18 Catawba RCP Coast Down

3.2.3.11.3. Rotation Torque Tests

The results of the first phase of the rotation torque testing are presented in Table 3-19 which shows the torque required to rotate the shaft in the dynamic tester under various pressure and temperature conditions. In all cases, the test is begun with the seal actuated and the shaft stationary. [

]^{a,b,c}

Table 3-19 Required Torque for Rotation

[

]^{a,b,c}

3.2.3.11.4. Slowly Rotating Shafts

[

] a,b,c

3.2.3.11.5. Full Speed Shaft Rotation

[

] a,b,c

[

]^{a,b,c}

[

] a,b,c

[

] a,b,c

3.2.3.11.6. Conclusions from Rotation Tests

The RCP No. 1 Seal, the SDS piston ring and the SDS polymer ring each offers unique features that aid in limiting the impact of an SDS inadvertently actuating on a rotating shaft, while protecting the SDS to enable it to perform its function in the event of an actual loss of all seal cooling. [

] a,b,c

3.2.3.11.7. Operator Response Margin

It is typical for a plant to have one or more alarms to alert the operator for a loss of CCW to the RCP and one or more alarms for a loss of seal injection to an RCP. However, the alarm language and the process parameter that causes the alarm can be different from one plant to another. For example, at one plant a loss of seal injection will result in a seal low dP alarm, but at another plant it will give a low seal injection flow alarm. For the CCW flow, at one plant there is a common alarm for CCW from the RCP (high CCW temperature or low CCW flow gives one common alarm), but at another plant it may be a low CCW flow to the RCP.

The operator response time can be determined by combining the purge times with the coast down times, [ ]^{a,b,c} to find the maximum response time for the operator to trip the RCP in order to ensure that the rotation of the shaft is stopped before the SDS actuates. Table 3-20 presents the results of this calculation for each pump model using the conservative calculation method in TB-04-22, Revision 1; alternate methods may be used by utilities to provide a more realistic time.

[

]^{a,b,c}

Table 3-20 Operator Response Margin for Tripping the RCP

a,b,c

[

] a,b,c

3.2.3.12 Scratch Tests

Data were gathered in the autumn 2008 outage season on various RCP sleeves and shafts to determine what surface conditions could be expected in the area where the SDS must seal. Sleeves and shafts can experience slight surface damage during the assembly/disassembly process. Although these minor defects do not hinder the operation of the standard controlled leakage seals the defects could potentially provide a leak path once the SDS has activated. Technicians who were performing standard seal maintenance at site were asked to record the surface finish, measure the sleeve/shaft for out-of-roundness, document defects (i.e., scratches, nicks, dings, etc.) and take pictures/video of the shafts/sleeves. Technicians were given instructions on how to record the desired information via model specific procedures.

The data taken in the field was used as input to tests where the SDS was subjected to scratch conditions equal to or worse than those found in the field.

The third component of this effort is to intentionally create defects that the SDS cannot seal against and develop a repair plan/technique that can be implemented in the field. This process will be necessary in the event that major shaft defects are found on the surface but the shaft remains structurally sound.

3.2.3.12.1. Field Data

Data from four plants were provided by field technicians on the condition of the RCP shafts or sleeves in the position where the SDS will eventually actuate. Fully measuring and detailing defects proved to be somewhat difficult due to the work conditions (poor lighting, difficult to access, heavy gloves, etc.). Though limited, these data do provide a reference point for what the SDS may be required to seal against in other plants.

[

] a,b,c

3.2.3.12.2. Testing of Scratches

In order to test how much damage the sleeve/shaft would tolerate before the SDS experienced excessive leakage, a series of scratched sleeves were manufactured. [

] a,b,c

Table 3-21 Summary of Results from Scratch Testing

a,b,c

[

] a,b,c

a,b,c

Figure 3-11 Predicted and Actual Leak Rates vs. Scratch Cross-Sectional Area

3.2.3.13 No. 1 Insert Integrity

The No. 1 Insert in the Reactor Coolant Pump will be modified to accept an SDS. The modified No. 1 Insert must be able to maintain its structural integrity during normal and faulted conditions.

3.2.3.13.1. No. 1 Insert Finite Element Analysis

A three-dimensional (3-D) finite element analysis (FEA) model was created, and two computer runs made, to simulate the two operating conditions. The results show that the component will not experience material yielding (i.e., permanent deformation) during either of these operating conditions.

Table 3-22 below summarizes the maximum stress intensity (SI) calculated by the FEA computer runs for the two operating conditions, normal and faulted, compared to the yield strength of the material allowable (Sy).

[

] a,b,c

Table 3-22 Maximum SI vs. Sy Allowable and Fatigue Usage Ratio

[

] a,b,c

3.2.3.13.2. No. 1 Insert Test

A full-scale accident condition test was performed on the Westinghouse SDS. This test was run at 570°F and 2300 psig for a total period of 29 hours. The No.1 Seal Insert was a production part modified as necessary for use in the SDS. A dimensional and visual inspection of the insert was performed after the test to demonstrate that it was not structurally deficient and also to validate the results of a FEA model used to analyze the Insert.

No dimensions were found to be outside of the original drawing tolerances in the post-accident condition inspection. [

] a,b,c

Table 3-23 Results from Post-SBO Inspection of Modified No. 1 Insert

[

] a,b,c

There was no difficulty removing the insert from the test machine or the internal components from the insert body. This indicates the lack of distortion or dimensional change.

3.2.3.14 Vibration Testing

Vibration tests were performed on complete SDS assemblies to determine whether they are affected by vibration during normal RCP operation, or during a design basis seismic event. The test parameters were selected to comply with nuclear qualification standards used by Westinghouse for safety related equipment. The SDS assemblies were examined for inadvertent actuation due to vibration and then heated as an assembly in an oven to actuation temperature to assure that it remained functional. In addition, the interface surfaces between components of the SDS were marked with a marking pen. Following the tests, the SDS was disassembled and examined to determine if there was any motion between the components of the SDS.

[

] ^{a,b,c}

Table 3-24 Seismic Test Accelerations

a,b,c

3.2.3.15 RCS Chemistry

The effects of system chemistry were studied on the thermal pistons, piston rings, retracting actuators, and polymer rings. The RCS chemistry that would be experienced by the SDS during startup, operation and shutdown is that of the seal injection water. During chemical additions, the seal injection water chemistry is the same as normal charging and may include high concentrations for various chemicals as they are introduced into the RCS. The chemistry investigated included RCS boric acid concentrations at mid-cycle and the boric acid concentrations during boration for shutdown at the end of a fuel cycle. Chemistry also included startup and/or shutdown levels of zinc, hydrogen peroxide (H_2O_2) and hydrazine.

Zinc

Zinc is used for control build-up of radioactive crud during plant operation and its release at plant shutdown. [

] ^{a,b,c}

Boron and Lithium Hydroxide

[

] a,b,c

Hydrazine

At plant start-up hydrazine is used to scavenge excess oxygen from the RCS and is injected into the RCS via normal charging, which will also include seal injection. Thus, the SDS may be exposed to high levels of hydrazine at plant start-up. [

] a,b,c

Hydrogen Peroxide

At plant shutdown hydrogen peroxide is injected into the RCS via normal charging, which will also include seal injection. Thus, the SDS may be exposed to high levels of hydrogen peroxide at plant start-up. Hydrogen peroxide is used to degas (hydrogen) the RCS prior to opening the RCS to atmosphere. Also the chemical is added for forced oxidation to create a controlled release of corrosion products (crud burst) from the RCS for cleanup prior to shutdown. A typical concentration in the RCS during a shutdown is 3 ppm with a maximum of 10 ppm. During peroxide addition, the concentration might be as high as 30% for a few seconds.

[

] a,b,c

3.2.3.16 Crud Exposure

The effects of crud on the components and the SDS as an assembly were studied. Although the seal environment is specified to be filtered to at least 5 microns, there have been occasions when crud bursts have resulted in crud entering the seal environment.

[

] a,b,c

3.2.3.17 Vacuum Testing

During start-up of the plant the system must be vented and purged of air. To do this, a vacuum is pulled on the system (referred to as the "vacuum fill" procedure). The only SDS component that might be susceptible to negative pressure would be the Retracting Actuator with its O-ring sealed thermal piston.

[

] a,b,c

3.2.4 Secondary Seal Integrity

[

] a,b,c

[

] a,b,c

[

] a,b,c

3.2.5 Summary of Testing Results

The ability of the SDS to meet the reliability goals has been demonstrated through testing and analysis of the SDS. The reliability goals include:

- Very low potential for inadvertent actuation during normal operation to ensure that the initiating event frequency for inadvertent actuation does not contribute to the PRA initiating event frequencies, as well as for plant asset management considerations.
- Passive activation at a No. 1 seal leak-off temperature of 250°F to 290°F to ensure sufficient time for the operators to trip the RCP motors using existing procedures and guidance and to ensure that a significant increase in RCS inventory loss through the RCP seals does not occur prior to activation of the SDS.
- Less than 1 gpm leakage following activation to eliminate the need for immediate manual operator actions to restore RCS makeup for Appendix R fire scenarios and station blackout scenarios.

The reliability for the Shut Down Seal that is demonstrated through testing and analysis is: [

] a,b,c

3.3 PRA MODEL

The current PRA model for RCP seal performance following a loss of all RCP seal cooling is the WOG2000 model described in WCAP-15603-A, Revision 1. This PRA model is based on the RCP seal behavior described in WCAP-10541 and assumes that the RCS inventory loss through the RCP seals increases to a minimum of 21 gpm at 13 minutes after a loss of all seal cooling. The change in RCS inventory loss from the pre-event value of 1.5 to 5 gpm to 21 gpm is due to thermally induced changes in the seal geometry and the change in the viscosity of water at elevated temperatures. Based on additional information developed by an NRC consultant, the WOG2000 model assumes that there is a 21% probability that the RCS inventory loss will be greater than 21 gpm due to either "popping" of the No. 2 seal (a 182 gpm leak rate) or "binding" of the No. 1 seal (a 480 gpm leak rate). The WOG2000 model also takes no credit for the No. 3 seal whether it is the bellow seal design or the cartridge seal design. Finally, the WOG2000 model assumes that the O-rings can fail by extrusion if the RCS pressure is not reduced to less than 1710 psig within 2 hours of the loss of RCP seal cooling.

Also, the PRA initiating event analysis for individual plants sometimes includes the two RCP seal LOCAs from the early 1980's (see Reference 4 for a description) that resulted in significant leak rates of RCS inventory to containment through damaged RCP seals. It is noted that Table 8-1 of NUREG-6928 (Reference 7) no longer counts these failures due to improvements in RCP seal design since those events.

Because the SDS stops flow before the No. 1 seal leak-off line and before the No. 2 RCP seal, successful actuation of the SDS prevents all of the RCS inventory loss pathways in the WOG2000 model. Therefore the RCP seal PRA model for plants with an SDS installed would be significantly altered as described below.

3.3.1 PRA Model Failure Modes

Based on the FMEA for the SDS presented in this report and the testing and analysis to quantify the probability of the possible failure modes, an event tree describing the behavior of the RCP seal package with the SDS installed can be constructed as shown in Figure 3-12.

In Figure 3-12, the upper path at each event denotes success and the lower path denotes failure. For example, for the top event "SDS Actuates", the upper path denotes successful actuation and the lower path denotes failure to actuate.

The top events in the event tree and their success criteria are defined as:

[

] a,c

a,c

Figure 3-12 RCP Seal Leakage With SDS Installed

[

] a,c

The outcomes for each path in the Figure 3-12 event tree were determined as follows:

[

] a,c

3.3.2 PRA Model Failure Probabilities

The split fractions assigned to the event tree nodes are supported by the statistical results of the testing program for the SDS that are described in this report.

[

] a,b,c

[

] a,b,c

[

]^{a,b,c}

[

] ^{a,c}

The PRA model does not need to be modified to account for inadvertent actuation of the SDS. As discussed in Section 3.2.3.11, inadvertent actuation of the SDS onto a rotating shaft at 1200 RPM in the absence of a loss of RCP seal cooling would not cause the SDS polymer to constrict against the shaft / sleeve and the operators would have sufficient feedback to diagnose the condition and bring the plant to an orderly shutdown without damage to any other components. Thus, inadvertent actuation would not cause a plant trip or any other initiating event normally considered in the PRA. In addition, the inadvertent actuation of the SDS is extremely unlikely. Therefore, the PRA model does not need to be modified to account for inadvertent actuation of the SDS.

3.3.3 Simplified PRA Model

The event tree shown in Figure 3-13 was developed to illustrate the elements of successful actuation of the SDS to limit RCS leakage to very low levels. The detailed model shown in Figure 3-13 was not intended to be implemented into plant specific PRA models.

a,c

Figure 3-13 SDS Leakage Probabilities

Rather it was intended that a very simple event tree or fault tree would be implemented directly in preceding the existing RCP seal model that asks two questions:

Does the SDS actuate and effectively seal on the pump shaft?

[

] a,c

Is the reactor coolant pump tripped within the operator response margin?

For a station blackout event, the response to this question is always true because AC power is lost to the RCPs as the initiating event. For all other sequences, a human error probability needs to be determined for the operator action to trip the pump so that the SDS is actuated on a stopped or slowly rotating shaft. The cues for the operator action and the typical times available to trip the pump motors can be found in Section 3.2.3.11.7 of this report. As discussed earlier, alternate methods to determine a more realistic time available for RCP trip can also be used. [

] a,c

3.3.4 Discussion of Uncertainties

The ASME/ANS PRA Standard (Reference 8) requires that the model uncertainties be identified and characterized so that they may be investigated further for risk-informed decision making. In some instances below, additional testing is referred to that which would substantially decrease identified uncertainties in the SDS PRA model. It is expected that the additional test information will have no impact on the SDS PRA model presented in this section of the report.

The model uncertainties that can affect the performance of the Shut Down Seal are identified as:

[

] a,b,c

[

] a,b,c

[

] a,c

3.4 DETERMINISTIC MODEL

The current model for RCP seal performance following a loss of all RCP seal cooling that is used in design basis and/or licensing basis analyses is a 21 gpm per pump leak. This is used in determining the acceptability of coping strategies for Appendix R and station blackout compliance and may be used in other deterministic analyses.

For plants installing the SDS, the design basis and licensing basis analyses can be changed based on a 1 gpm per pump leakage rate, consistent with the design basis requirements for the SDS. The use of 1 gpm per pump provides a large margin to the expected performance of the SDS and therefore added assurance for these types of analyses. This change is contingent on the licensee's ability to show that the RCP will be tripped in a timely manner, as shown in Table 3-20, after a loss of all RCP seal cooling is diagnosed.

In addition, an actuated SDS prevents flow of colder water to the RCP seal package in the event that seal injection is restored. Therefore, restoration of seal injection after a loss of all seal cooling event does not affect the performance of the SDS due to cold thermal shock. Therefore, there should no longer be limitations on restoration of seal injection with respect to SDS performance. Also, limitations on RCS cooldown rates to less than 100°F per hour, as discussed in TB-04-22, Revision 1, are no longer applicable.

The Westinghouse SDS is designed and manufactured as a safety related component subject to the NRC special treatment requirements of 10 CFR Part 50. This supports those utilities that procure the entire RCP seal package as a safety related component.

The Westinghouse SDS is not designed as an RCS pressure boundary component. The SDS has no RCS pressure boundary function in its normal non-actuated state. Once actuated for a loss of all RCP seal cooling event, the SDS is designed to be effective for events in which a secondary side heat sink is maintained via a long term steam generator feed. Thus, the maximum RCS pressure would be limited to a value below the pressurizer relief or safety valve setpoint. [

] ^{a,c} Also, the failure of the SDS to either actuate or to seal will result in reliance on the existing RCS pressure boundary components since no change is being made to the existing RCP components and the SDS does not interfere with their design basis RCS pressure boundary function.

The SDS has been extensively tested in the environment that is representative of the environment in which it will perform its design basis function [

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It is also tested in the environment that it will be exposed to for its lifetime (RCP seal injection water) to assure that there are no detrimental impacts. In addition, each Shut Down Seal retracting actuator and piston ring will be tested prior to installation to confirm that it will function as designed. While this does not constitute a formal environmental qualification program, the testing described in this report and the pre-installation functional testing provides a high degree of confidence that the Shut Down Seal will perform its design basis function in the environment that it will be required to perform. Finally, the actuation of the SDS does not interfere with natural circulation cooling of the RCS. [

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3.5 PROCEDURES

3.5.1 Emergency Operating Procedures

There are currently three limitations in the generic Westinghouse Emergency Response Guidelines (ERGs) related to the current RCP seals. The ERGs provide a consistent basis for the development of plant specific Emergency Operating Procedures (EOPs). Similar limitations may also be included in Abnormal Operating Procedures at individual plants, such as response to fires, response to loss of CCW or response to loss of SW. The limitations are:

- Restrictions on re-establishing seal injection if RCP seal cooling has been lost and the temperatures exceed the criteria for RCP shut down.
- Restriction on cooling down the RCS following a loss of all seal cooling event to less than or equal to 100°F per hour to prevent thermal shock to the RCP seal package.
- The need to cooldown and depressurize the RCS following a loss of all seal cooling event to minimize RCS inventory loss through the RCP seals and therefore maximize recovery time.

These limitations can remain in the generic procedures following installation of the SDS because they have no impact on the SDS performance. However, these limitations can be removed since the SDS restricts flow through the seal package when actuated and therefore the RCS inventory loss and the effect of thermal shock on the seal leakage are eliminated.

A change to the generic Westinghouse ERGs has been approved for implementation by utilities installing the Shut Down Seal. The change entails adding instructions to have the operating crew determine if an immediate plant cooldown is required based on RCS subcooling, pressurizer level, and time since RCP seal cooling was lost. A steady pressurizer level indicates that the SDS has actuated and RCS inventory losses are minimal. The subcooling indicates that heat removal via the SGs is effective. The time criteria would be based on the plant's SBO coping time (i.e., loss of all DC instrument power) or 8 hours. The 8 hours was selected to provide margin time to initiate RCS cooldown and inject borated inventory from SI accumulators prior to peak xenon decay 12 hours after reactor trip.

The Emergency and Abnormal procedure steps to stop the RCP upon loss of all seal cooling if the seal or bearing temperatures exceed the shut down limits are very important to assure the survivability of the SDS. This will be emphasized in the Instruction Manuals that accompany the SDS when installed at a plant.

The generic Westinghouse Emergency Response Guideline for bumping the RCP in the FR-C.1 Response to Core Cooling guideline remains unaffected by the installation of the SDS. In this case, the core is already overheated and the RCP is "bumped" to attempt to inject the contents of the "cross-over" or intermediate leg into the core to delay the core heatup progression. This is beyond the design basis of the current seal package as well as the SDS and the consequences of this action are undetermined. In this case, the current seal package may be damaged and develop excessive leakage. The addition of the SDS does not change this, but may limit any additional leakage. Therefore, this guidance does not need to be re-visited.

3.5.2 Abnormal Operating Procedures

The AOPs would typically provide operator guidance for fires, loss of CCW and loss of SW events that can result in a loss of RCP seal cooling. Since typical AOPs are plant specific and do not rely on a common basis similar to the ERGs, the contents may vary from plant to plant. However, the important characteristics of the AOPs can be identified as:

- Rapid diagnosis of a loss of seal cooling event followed by prompt tripping of the reactor coolant pumps.
- Do not turn "on" oil lift pumps to aid in natural circulation cooling of the reactor core when all RCP seal cooling is lost.

3.5.3 Start-Up Procedures

The plant start-up procedures provide guidance on the use of the oil lift pumps during initial RCP start from cold shut down. The oil lift pumps are used to aid in starting the RCPs and are then typically turned "off" and not used again. The start-up procedures should be reviewed to confirm that the operators are instructed to turn off the oil lift pump after the RCP is started, in accordance with the RCP vendor's Instruction Manual.

4. LIMITATIONS AND CONDITIONS FOR ACCEPTANCE

The limitations for the acceptance of the SDS PRA model described in this report are:

- Review of the applicable operating procedures to confirm that:
    - Operator guidance is provided to promptly trip the RCPs on the loss of all RCP seal cooling.
    - Control room readouts and alarms for loss of all RCP seal cooling are consistent with the assumptions in the PRA model for operator actions.
    - The oil lift pumps are not used except for plant start-up.
- The control room readouts and alarms for loss of RCP seal cooling are functionally tested and calibrated.
- Operation with Shut Down Seals within their qualified 9-year service life.
- The SDS package described in this report is for the 93A RCP model. Small differences in the SDS package may be necessary for other pump models. Some additional testing may be done by Westinghouse to confirm that the SDS for these other RCP models performs to the specifications described in this report. Therefore, the PRA and deterministic models described in this report are applicable to installation of a Westinghouse SDS package in all Westinghouse RCP models.

5. SUMMARY AND CONCLUSIONS

Westinghouse has developed a reactor coolant pump Shut Down Seal that restricts reactor coolant system inventory losses to very small leakage rates in the event of a plant event that results in the loss of all RCP seal cooling. The SDS is a thermally actuated, passive device that is installed between the No. 1 seal and the No. 1 seal leak-off line to provide a leak-tight seal in the event of a loss of all RCP seal cooling. The installation of the SDS will permit plants to respond to a wide range of events with only an AC independent auxiliary feedwater pump available. The possible events include station blackout, fires that disrupt power supplies, loss of component cooling system and loss of service water system. Because there would be negligible RCS inventory losses through the RCP seals, RCS makeup is no longer necessary to achieve a stable state with the reactor core being cooled.

The current PRA model for RCP seal performance is the WOG2000 model that has been reviewed and approved by the Nuclear Regulatory Commission as a "consensus" model for use in the PRA. Risk-informed applications derived from PRA studies using the WOG2000 model have become part of the fabric of plant operation and includes daily plant configuration risk management activities, Mitigating System Performance Index reporting, regulatory submittals for change to the plant Technical Specifications, and regulatory interactions during Significance Determination Process proceedings.

Plants installing the Westinghouse SDS will likely change their Probabilistic Risk Assessment to credit this enhanced safety capability. The current WOG2000 model will be supplanted by a new SDS model in the PRA. The revised PRA can then be used to modify risk-informed applications in use by the plant. In order to conserve utility and NRC resources in reviewing PRA models used for regulatory interactions, the PRA model for the SDS is being submitted to the NRC for review and approval. The actual change to the plant will require each licensee to perform a 10 CFR 50.59 assessment to determine if prior NRC approval is required for installation of the SDS.

The performance of the SDS has been verified by a large amount of testing and analysis to confirm that it meets very stringent design goals. The testing has included individual component tests as well as tests of the entire seal assembly under conditions that exceed those that are predicted for a station blackout event. The extensive testing allows the assignment of a statistically based PRA probability for the SDS failure to actuate and seal to very low leakage levels of less than 1 chance in one hundred. The testing has also shown that the likelihood of inadvertent actuation is extremely small and will not result in conditions adverse to safety. In addition, testing has shown that inadvertent actuation at low seal injection temperatures would not prevent the SDS from effectively limiting RCS inventory loss via RCP seal leakage in the event of a subsequent loss of all seal cooling event.

The PRA model developed for the SDS is based on the failure modes and effects analysis and the subsequent testing and analysis. The statistically based failure probability for the SDS to fail to actuate and seal to very low leakage will result in a significant decrease in core damage frequency predicted from the PRA. The actual reduction will vary from plant to plant depending on the contribution of the RCP seals to the core damage risk metric.

In addition to the reduction in the PRA risk metrics, the installation of the SDS may also permit utilities to modify their coping strategies for station blackout and fires as required by 10 CFR 50.63 and Appendix R to 10 CFR 50 respectively. By eliminating a source of RCS inventory loss, the SDS may also have beneficial effects for mitigating strategies designed to cope with security related events. It is proposed that plants installing the SDS can modify their design and/or licensing basis analyses for the RCP seal performance under a loss of all RCP seal cooling event by using an RCP seal leak rate of 1 gpm for the duration of the event. This report also seeks NRC review and approval of that analysis model for the SDS in design and licensing basis analyses to facilitate NRC review of these revised analyses. It is recognized that plants will be required to submit revised design basis or licensing basis analyses to the NRC for plant specific approval; the NRC acceptance of the design / licensing basis Shut Down Seal performance will facilitate those reviews.

Finally, the current plant Emergency Operating Procedures and Abnormal Operating Procedures contain several steps to protect the existing RCP seals that would no longer be necessary after the SDS is installed. The SDS eliminates concern over rapid thermal transients at the RCP seals because SDS controls leakage and is not sensitive to thermal shock. Also, rapid operator actions to initiate and control an aggressive RCS cooldown and depressurization to limit RCP seal leakage are no longer necessary. Thus operator performance in responding to events that result in a loss of RCP seal cooling can be enhanced by removing those procedure steps. However, the procedure steps to trip the RCPs upon a loss of RCP seal cooling remain necessary for proper functioning of the RCP seals, including the SDS. These procedure step changes will be controlled by the plant 10 CFR 50.59 assessment process to determine whether NRC review and approval is required.

6. REFERENCES

1. WCAP-10541, Revision 2, "Reactor Coolant Pump Seal Performance Following a Loss of All AC Power," Westinghouse Electric Co., November 1986.
2. WCAP-15603, Revision 1-A, "WOG 2000 Reactor Coolant Pump Seal Leakage Model for Westinghouse PWRs," Westinghouse Electric Co., June 2003.
3. TB-04-22, Revision 1, "Reactor Coolant Pump Seal Performance – Appendix R Compliance and Loss of All Seal Cooling," Westinghouse Electric Co., August 9, 2005.
4. WCAP-16396-NP, "Westinghouse Owners Group Reactor Coolant Pump Seal Performance for Appendix R Assessments," Westinghouse Electric Co., January 2005.
5. WCAP-10541, Revision 2, Supplement 1, "High Temperature Extrusion Qualification Testing of Seals Eastern 7228A O-Ring Compound: Supplemental Information to Westinghouse Owners Group Report Reactor Coolant Pump Seal Performance Following a Loss of All AC Power," Westinghouse Electric Co., 1988.
6. NUREG/CR-6823, "Handbook of Parameter Estimation for Probabilistic Risk Assessment," U.S. Nuclear Regulatory Commission, September 2003.
7. NUREG-6928, "Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants," Nuclear Regulatory Commission, February 2007.
8. ASME / ANS RA-Sa-2009, "Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear power Plant Applications," 2009.

APPENDIX A – OTHER IMPACTS OF SDS

1.0 Impact on Current PRA Models

The installation of the SDS in a plant is expected to result in a significant reduction in the predicted CDF in the internal initiating events, fire, seismic and external events PRAs.

Figure A-1 provides the results of a survey of plants with Westinghouse RCPs to determine the contribution to CDF from RCP Seal LOCAs. The figure shows that the CDF reduction that is possible by eliminating RCP seal leakage for all events that result in a loss of all RCP seal cooling is very plant dependent. The reduction could range from as much as 80% to as little as 5%. The median CDF reduction for those plants in the survey is 35% and the mean CDF reduction is 39%. It is noted that the Plant F which reports only a 5% reduction takes credit for a dedicated seal injection system that automatically starts on a loss of seal injection.

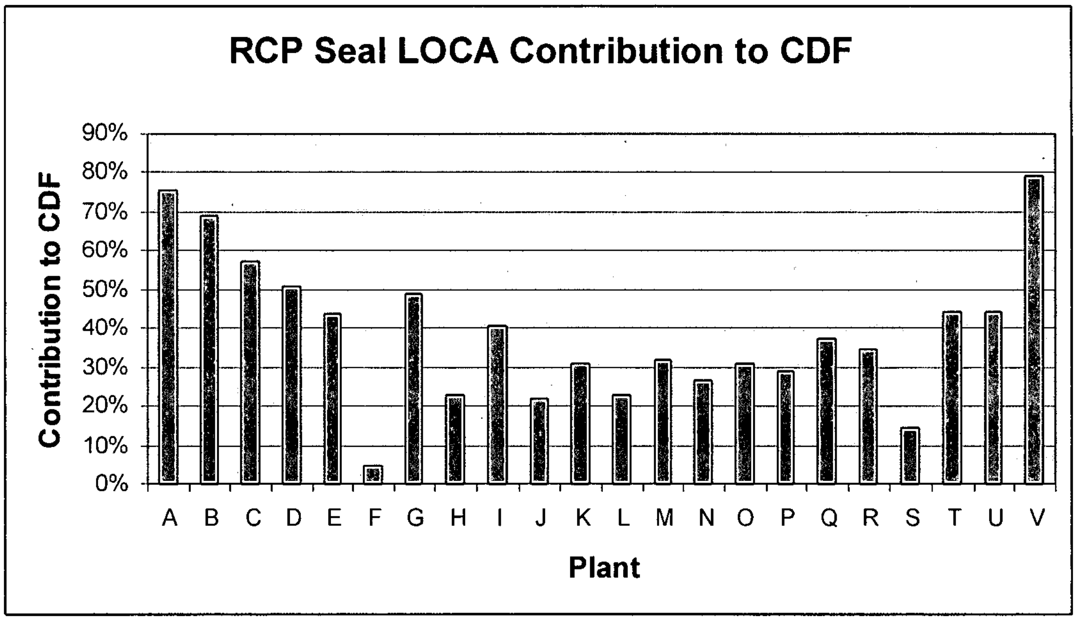

Figure A-1 RCP Seal LOCA Contribution To Core Damage

Another way to estimate the potential improvement in risk for installation of the Shut Down Seal is to study the initiating event contributions to core damage. Figures A-2 and A-3 show the contributions to core damage for two plants with Westinghouse RCPs.

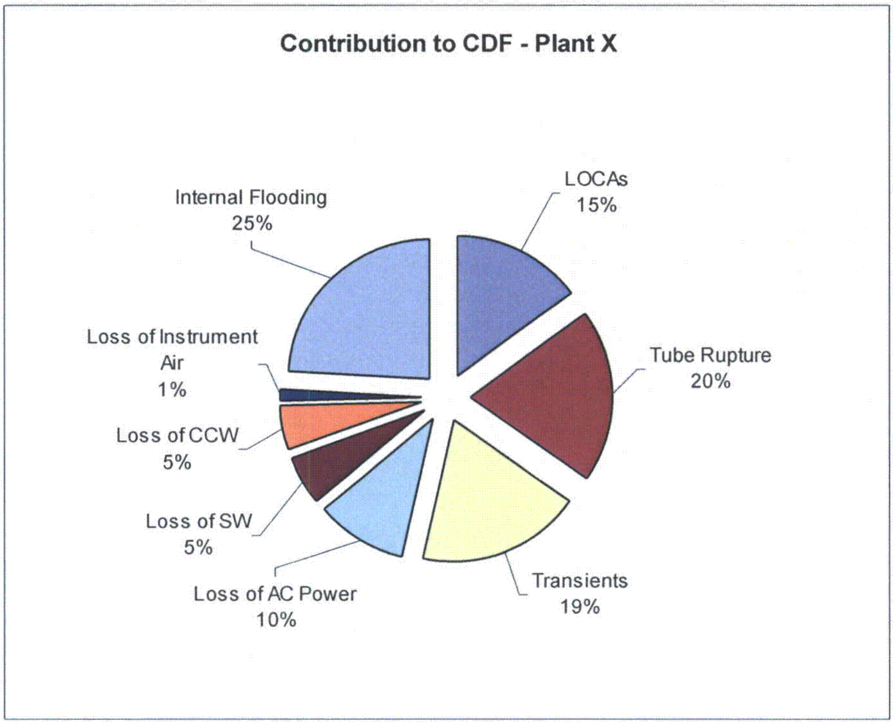

Figure A-2 Contributors To Core Damage for Plant X

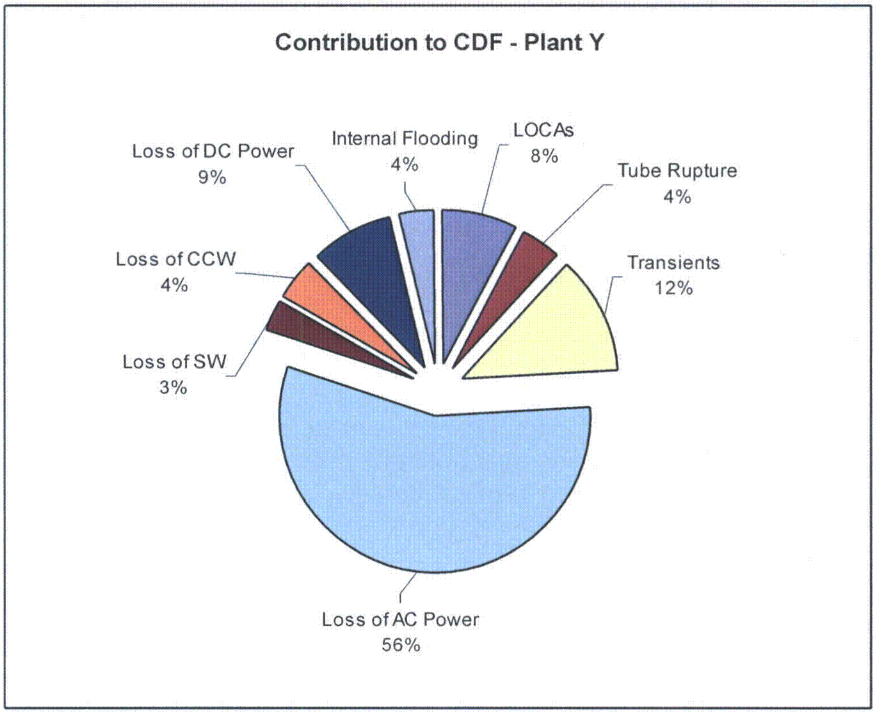

Figure A-3 Contributors To Core Damage for Plant Y

The initiating events that contribute to the loss of RCP seal cooling are typically:

- The loss of AC power event which can result in a loss of both CCW pumps for thermal barrier cooling and charging pumps seal injection,
- The loss of CCW event which can result in a loss of thermal barrier cooling and, for some plants the loss of charging pump cooling,
- The loss of SW event which results in a loss of CCW and a loss of charging pump cooling for some plants, and
- The loss of DC power which results in a loss of control of vital plant processes.

The initiating event contributions alone can over-state the importance of RCP seal cooling because not all loss of AC power, CCW, SW or DC power lead to core damage because of RCP seal leakage. Recovery of these functions before core damage occurs is an important consideration in the PRA model.

The initiating event contributions also do not accurately portray the possible reduction in core damage because even with perfect RCP seals, core damage may still occur for some fraction of these initiating events. For example, for the station blackout events, if AC power is not recovered before the station batteries are depleted, the ability to control auxiliary feedwater from the control room to maintain a steam generator (SG) inventory would be lost and core damage could occur as a result of a loss of heat sink and RCS inventory losses through the pressurizer relief or safety valve, even though there is no reactor coolant pump seal leakage.

Therefore, the best indication of the risk importance of the Westinghouse SDS can be obtained from the RCP seal LOCA contribution to core damage as shown in Figure A-1. This figure shows that the expected reduction in core damage across the Westinghouse Pressurized Water Reactor (PWR) fleet would be on the order of 35% with several plants at over 50%.

2.0 Impact on Risk-Informed Applications

The reduction in overall CDF and the significant reduction in the importance of seal cooling for prevention of core damage is expected to have a significant impact on the following risk-informed regulatory applications:

Configuration Risk Management (CRM): CRM refers to the scheduling of maintenance on plant components to understand and manage the impact of components out-of-service for repair, periodic maintenance, testing or surveillance. The goal of CRM is to manage plant risk by assuring that risk significant combinations of diverse components are not out-of-service simultaneously (or that the out-of-service time is minimized). For example, a risk significant combination of components might be a charging pump and the AC independent auxiliary feedwater pump. In the event of a loss of offsite power, the mitigation capability of the plant would be significantly diminished by having this combination of components out-of-service simultaneously.

With the installation of the Shut Down Seal, the importance of providing continued RCP seal injection with the charging pump may be significantly reduced. Thus, installation of the SDS may change the risk important combinations of out-of-service components.

Mitigating System Performance Index (MSPI): MSPI is a performance indicator in the NRC Reactor Oversight Cornerstones that focuses on the availability of risk important systems. In particular, MSPI measures the availability of certain systems and their key components that are important to risk: Cooling Water, Emergency AC Power, Decay Heat Removal, Safety Injection and Auxiliary Feedwater. MSPI is a measure of availability of these systems and is related to the importance of the systems at each plant. Failures of components during operation or during periodic surveillance testing can decrease the margin available to regulatory targets of availability.

With the installation of the Shut Down Seal, it is expected that the importance of the charging system and component cooling system will decrease in MSPI space. However, because MSPI is based on relative contributions to risk for a particular plant, the margins for availability for auxiliary feedwater may decrease since only the AC independent auxiliary feedwater system will now become important for preventing core damage for many more initiating events.

Risk-Informed Technical Specifications: Allowable Outage Times (AOTs) and Surveillance Test Intervals (STIs) are increasingly becoming a function of risk. This is especially true for Risk-Informed Technical Specification initiatives 4b and 5b where AOTs and STIs are tied directly to the plant PRA model.

With the installation of the Shut Down Seal, it is expected that AOTs and STIs for systems would be able to be extended due to the decreased risk importance of these systems.

APPENDIX B – SUMMARY OF SDS TESTING

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