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Revision 1

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Use of Westinghouse SHIELD® Passive Shutdown Seal for FLEX Strategies

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RECORD OF REVISIONS

Revision	Date	Revision Description
0	March 2014	Original Issue
1	March 2014	[ ]a,c Several uses of word "ensure" removed. Footnote 1 on page 5-1 made proprietary to retain consistency.

Executive Summary

The Westinghouse **SHIELD**® Passive Thermal Shutdown Seal (SDS) is a low-leakage seal product designed to limit reactor coolant system (RCS) fluid leakage through the existing Westinghouse reactor coolant pump (RCP) seals to less than 1 gallon per minute (gpm) per pump. The SDS is passively activated by a loss of all seal cooling (LOASC) that would occur as a result of a station blackout (SBO) or extended loss of alternating current (ac) power (ELAP) and, therefore, requires no operator action for deployment. It is specifically designed to maintain RCS inventory and support extended core cooling strategies. The Westinghouse SDS has (1) significant operating experience (OpE), (2) a systematic environmental testing program, and (3) undergone a robust design and qualification process that demonstrates the SDS is a reliable product to passively limit RCS leakage during LOASC events. This technical report provides a comprehensive summary of the design, analysis, qualification testing, and OpE necessary to support licensees' FLEX overall integrated plans (OIP).

The SDS is designed to operate passively within a designed, elevated temperature range outside the bounds of normal RCP seal operation. In the event of a LOASC, the SDS device's passive thermal actuator will retract and initiate closure of the SDS piston ring. The piston ring is designed to create a large pressure difference across the SDS polymer ring. The developed pressure within the seal compresses the polymer ring and creates a near leak tight seal.

Following the failures of the prior generations of the SDS, Westinghouse initiated the development of the Generation III SDS with renewed commitment to design a highly improved and reliable product encompassing OpE and extent-of-condition evaluation. This effort placed a significant emphasis on improved design process formality, rigor, and discipline at all levels of the organization. As an example, to bolster the rigor of the design process, Westinghouse requested the participation and services of a third-party independent engineering firm and utility representatives to provide unparalleled technical challenge and valuable OpE to the design review process. In doing so, the design process was expanded to revalidate design criteria, verify all assumptions, and perform an extent-of-condition evaluation with a heightened focus on corrosion and friction. As a result, the Generation III SDS design evolved to address the vulnerabilities identified in the previous generations, producing a more reliable product that is:

- Simpler
- Stronger
- Fortified against inadvertent actuation
- Highly resistant to RCS chemistry and particulate deposition
- Tested in severe conditions, exceeding the RCP OpE collected

Like the previous actuator, the new direct-acting actuator's operation relies on the expansion of wax; a process that operated successfully in the previous generations. However, unlike the previous designs, the force generated by the new actuator's design is not fixed. As the wax expands, it imparts a force that acts directly on the retracting actuator piston. The actuator will continue to generate more force as temperature increases or until the piston fully retracts.

In addition to the improved actuator, the design team has implemented other notable improvements to increase margins-to–failure, thus accommodating operating conditions much more severe that those recorded over the past decades of RCP operation. Based on the testing, it was determined that a chromium

coating on the wave spring and piston ring contacting surfaces gave optimal performance for piston ring closure within the simulated operating environment. This coating also has considerable OpE within the nuclear industry in applications subjected to reactor coolant fluid contact.

While the OpE collected would already suggest the Generation III SDS design will successfully operate without any additional modifications or testing, Westinghouse has taken this opportunity to optimize the design and expand the testing and analysis of the product. As part of that initiative and to improve the understanding of the SDS device's performance from a computational standpoint, two sophisticated models were built for analysis.

1. The first was a kinematic model that was validated against available test data as well as OpE. This model, capable of predicting Generation I and II sealing failures in severe condition testing, improved understanding of the SDS operation and allowed for optimization of the wave spring force and other design parameters to improve design margin.

2. The second model was developed to further understand and validate prior assumptions relative to the potential challenges the SDS faces when actuating onto an RCP shaft during coastdown. A nodal fluid model of the seal package was developed to evaluate time of actuation after a LOASC. This was referenced against a coastdown curve of the pump in a simulated LOASC event to determine the appropriate rotational speed to be used in dynamic testing of the SDS. Testing informed by this model was successfully carried out and is bounding for Westinghouse Model 93, 93A, and 93A-1 RCPs, assuring successful actuation and sealing. Furthermore, an SDS polymer ring from these tests was then tested to demonstrate that, despite minor wear from activating on a slowly spinning shaft, the polymer could successfully seal for 168 hours or longer. In the case of the tested ring, sealing has been successful for over 3 months at the time of writing this paper.

To further validate the Generation III design, the devices were tested in conditions that were more severe than those identified from OpE. These tests were completed in series such that all effects compounded onto one another. As a validation of the severity of the tests, the test conditions used for the Generation III qualification generate test failures in Generation I and II actuators. Additionally, many exploratory tests were conducted to determine the failure conditions for the SDS so that the design margins are known and have been validated against analytical calculations. This testing philosophy provides Westinghouse with a clear understanding of the capabilities, bounds, and perturbation response of the SDS assembly. It is for all of these reasons that Westinghouse is confident that device survivability under the Generation III testing plan is a credible predictor of the Generation III SDS device's future performance.

In conclusion, Westinghouse addressed the deficiencies of the Generation I and II devices, improved on their strengths, tested under severe in-service conditions capable of generating failure of previous generation devices, and showed consistent, reliable actuation and sealing in qualification testing for the Generation III SDS. Accordingly, there is a sound basis for confidence in utilizing the Westinghouse **SHIELD** Passive SDS in FLEX mitigation strategy responses.

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ACRONYMS AND TRADEMARKS

AC	alternating current
ACA	apparent cause analysis
CCW	component cooling water
CVCS	chemical and volume control system
DFMEA	design failure mode and effects analysis
EDM	electrical discharge machining
ELAP	extended loss of AC power
EPRI	Electric Power Research Institute
FENOC	First Energy Nuclear Operating Company
FS	factor of safety
fs	static friction coefficient
gpm	gallons per minute
ID	inside diameter
lbf	pounds force
LOASC	loss of all seal cooling
MCOE	Materials Center of Excellence
NRC	Nuclear Regulatory Commission
OBE	operating basis earthquake
OD	outside diameter
OI	open item
OIP	overall integrated plan
OpE	operating experience
PEEK	polyether ether ketone
PFMEA	process failure mode effects analysis
PH	precipitation-hardened
ppm	parts per million
PSD	power spectral density
psi	pounds/square inch
psia	pounds per square inch absolute
PWR	pressurized water reactor
QA	quality assurance
QMS	quality management system
Ra	roughness average
RCA	root cause analysis
RCCA	rod control cluster assembly
RCDT	reactor coolant drain tank
RCP	reactor coolant pump
RCS	reactor coolant system
rpm	revolutions per minute
SDS	shutdown seal
SFP	spent fuel pool
SNC	Southern Company
SSE	safe shutdown earthquake

ACRONYMS AND TRADEMARKS (cont.)

TBHX	thermal barrier heat exchanger
TVA	Tennessee Valley Authority
VCT	volume control tank

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1 PURPOSE OF DOCUMENT

The purpose of this white paper is to serve as a reference for the use of the **SHIELD** Passive Thermal Shutdown Seal (SDS) in utility FLEX implementation strategies (Reference 1) for reactor coolant pump (RCP) Models 93, 93A, and 93A-1, complying with U.S. Nuclear Regulatory Commission (NRC) Order EA-12-049 (Reference 2) and endorsed in JLD-ISG-2012-01 (Reference 3). Numerous Westinghouse utilities have credited a low-leakage RCP seal package in their FLEX overall integrated plan (OIP) submittals. This paper details the design improvements, design basis, and qualifications for the Generation III SHIELD, which can be used by the Regulator and utilities as FLEX implementation moves forward. This is critical due to the significant impact of RCP seal leakage when developing FLEX coping strategies. The assumed leakage of the RCP seal package impacts the key safety functions FLEX is designed to maintain either directly or indirectly as follows:

- Core Cooling
  - Reactor coolant system (RCS) cooldown and depressurization (higher RCP seal leakage requires earlier action to limit loss of RCS inventory, which impacts Phase 1 staffing requirements)
  - RCS inventory control (equipment sizing and timing of actions)
  - Borated water sources (how long installed sources will support RCS makeup)
  - Unborated water sources (RCS cooldown during Phase 1 depletes installed sources faster)
- Containment
  - Rate of change in pressure and temperature
- Spent fuel pool (SFP) Cooling
  - Borated water sources (allocation of limited borated water sources between RCS makeup and SFP makeup)
- With a complete installation of the SDS, the complexity of the extended loss of all alternating current (ac) (ELAP) transient and the operator burden is reduced

Utilities installing the new, Generation III SDS will require a reference for the FLEX OIP submittals and this white paper will serve as that document.

In order to understand the design basis and improvements to the Generation III SDS product, a comprehensive background must be established. Discussion of the technology, seal leakage issue, operating experience (OpE), and findings of the root cause analyses (RCA) of Generation I and Generation II SDS failures herein provides this background. Subsequently, a description of the design improvements made to the Generation III SDS is provided, including discussion of the design, expected function, pre-existing applicable testing, design improvements, and description of the Generation III qualification testing program.

This document demonstrates that the Generation III SDS will provide reliable actuation and sealing to reduce RCS inventory loss, given its OpE and design improvements.

2 BACKGROUND ON REACTOR COOLANT PUMPS AND SDS DESIGN

2.1 PURPOSE OF PUMP

During routine plant operation, the purpose of the RCP is to circulate reactor coolant at a rate adequate to remove the heat released by nuclear reactions in the core, while maintaining the fuel assemblies at a safe temperature. In addition, the RCP is equipped with a massive flywheel to allow pump rotation to continue for several minutes after the onset of an ELAP event. This is required because natural circulation alone is inadequate to remove the decay heat in the early minutes of a reactor trip. A detailed discussion of the RCP is provided in WCAP-10541 (Reference 4).

2.2 PUMP PARTS

The RCP consists of an impeller, diffuser, casing, thermal barrier heat exchanger (TBHX), lower radial bearing, main flange, and pump shaft (See Figure 2.2-2). The shaft is connected to a motor located vertically above this assembly. 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 a nominal 2,250 pounds per square inch absolute (psia) to containment ambient pressure. See Figure 2.2-1 for a diagram of the sealing system. The shaft is nominally 8 inches in diameter at the location of the No. 1 seal.

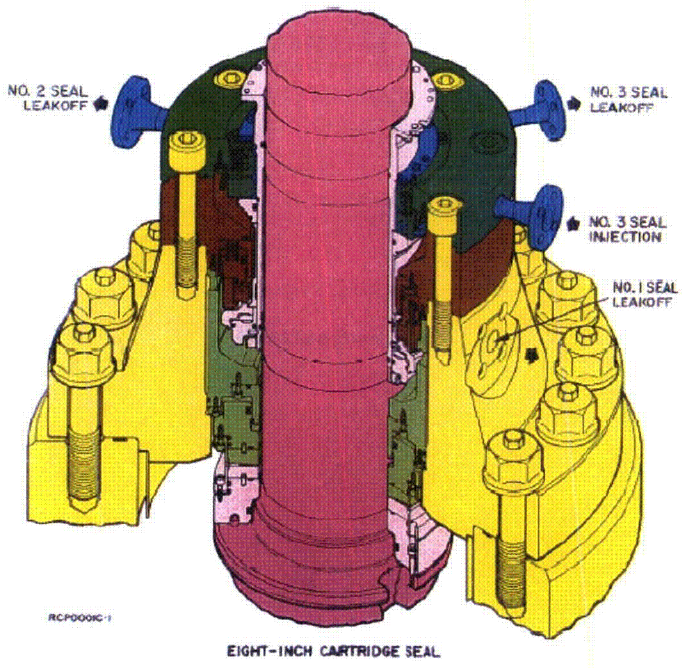

Figure 2.2-1 Diagram of 8-inch Cartridge Seal

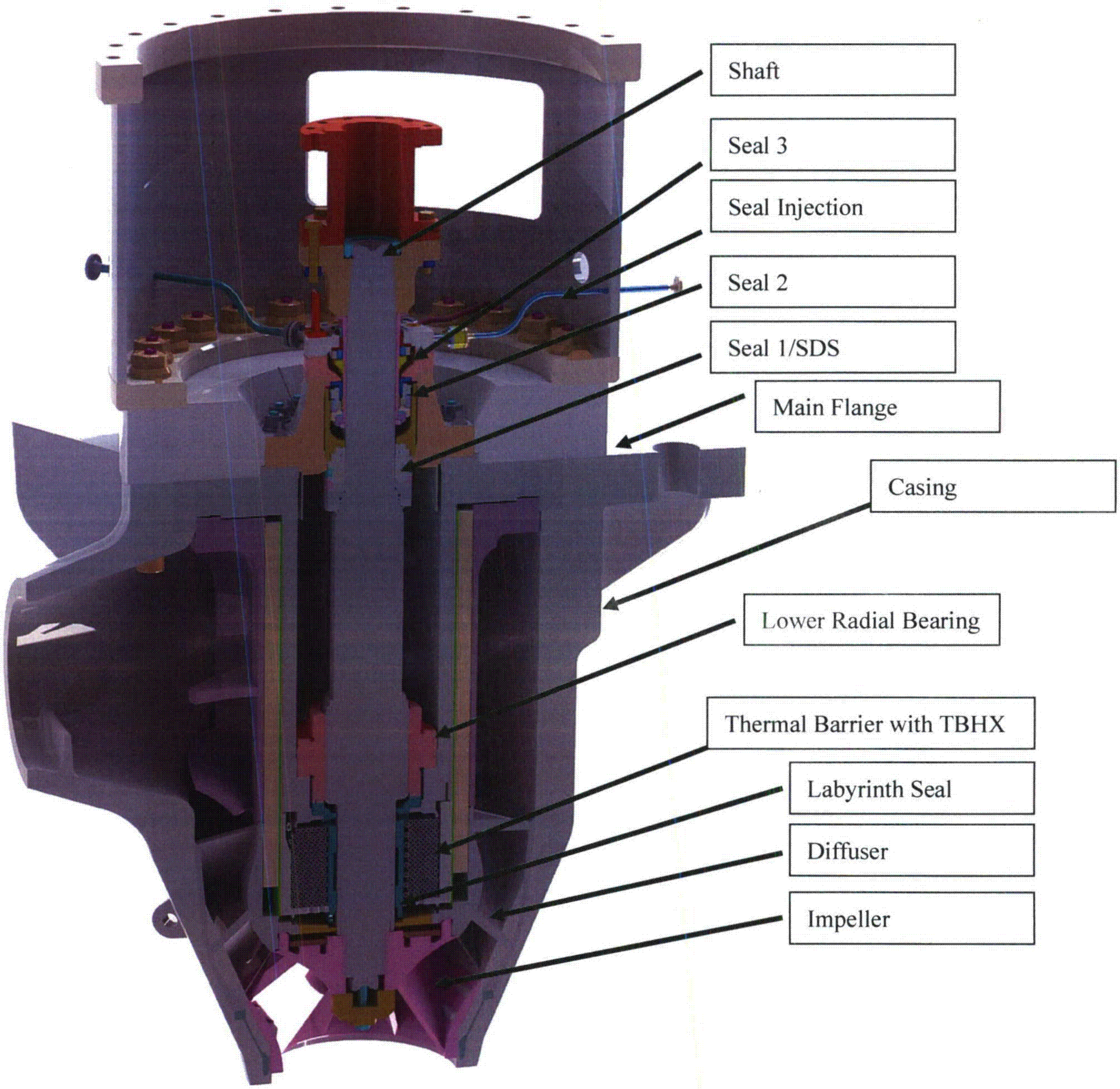

Figure 2.2-2 Cutaway of Reactor Coolant Pump and Seal Package

The impeller, diffuser, and casing are the parts that make up the actual pump in the traditional sense. The casing directs flow from the impeller to the diffuser and then to the outlet. The impeller imparts the fluid with high velocity and then the diffuser serves to align the flow and convert velocity into pressure.

The main flange fastens to the casing. The thermal barrier is situated between the main flange and casing and also fastens to the No. 1 seal housing.

A labyrinth seal is located in the thermal barrier cavity at the point where the shaft penetrates into the RCS. This seal impedes the high-velocity flow of the coolant into the thermal barrier, lower radial bearing, and seal package. The TBHX is also located within the thermal barrier cavity. As its name suggests, the thermal barrier prevents hot RCS fluid from reaching the bearings and seal package of the pump, damaging components, and flashing across zones of reducing pressure. It has two methods to achieve this during normal operation.

The first method is injection of low-temperature seal injection flow from the charging pumps into the thermal barrier cavity. Seal injection is typically at a pressure of nominally 2,250 psia and a temperature of 130°F. The total seal injection flow to each pump is typically 8 gallons per minute (gpm). The seal injection flow pushes through the labyrinth seal into the RCS, fundamentally preventing flow from the RCS into the thermal barrier. The amount and direction of injection flowing through the seals are functions of the specific conditions of the installed seal. Nominal flow through the No. 1 seal is 2 gpm. Therefore, the difference (6 gpm in this instance) is forced through the labyrinth seal into the RCS. Normal No. 1 seal operating range is 1 to 5 gpm. As the seal injection water is already at a low temperature, additional means of cooling are not required under normal conditions.

However, if this injection stops, a second means of cooling exists as redundancy. In this condition, component cooling water (CCW), by means of the previously mentioned TBHX, can provide sufficient cooling without interrupting plant operation.

2.3 SEAL PACKAGE

The Westinghouse RCP seal and flow paths are shown in Figure 2.3-1.

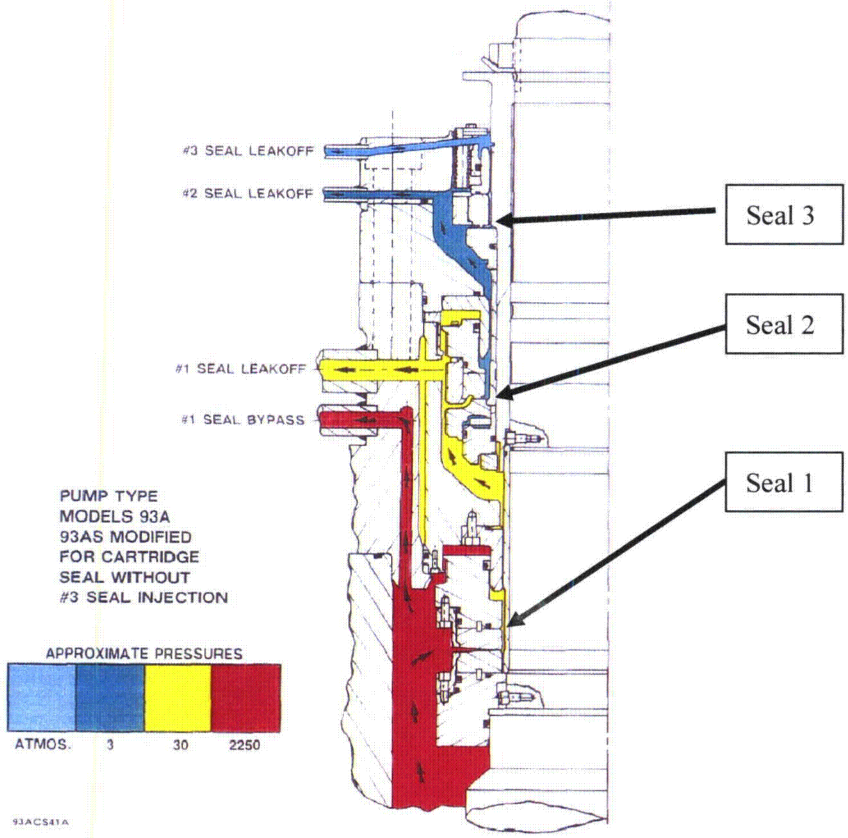

Figure 2.3-1 Westinghouse RCP Seal Diagram with Flow Paths

The No. 1 seal is the main seal on the pump. It is a controlled-leakage (hydrostatic), film-riding, radial taper face seal. The primary components are a runner that rotates with the shaft and a nonrotating seal ring that is attached to the seal housing or insert support, depending on the pump model. The seal ring can move axially to accommodate axial motions of the shaft. The pressure at the inlet to the seal is RCS pressure, while the pressure on the downstream side of the seal is controlled by the flow resistances in the No. 1 seal leakoff line and the volume control tank (VCT) pressure. The gap between the two seal faces is normally 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 during normal operating conditions. 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.

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 leakoff line. In the normal mode of operation, the No. 2 seal operates with a differential pressure of approximately 30 psi across the face. The inlet pressure on the seal is normally determined by the VCT pressure and the backpressure is determined by the head of water maintained

above the No. 2 seal leakoff connection and/or pressure in the reactor coolant drain tank (RCDT). When functioning as designed, the No. 2 seal will typically leak at a negligible rate (e.g., 3 gallons per hour) and any flow through the seal passes to the RCDT.

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 leakoff line. The normal leakage through the No. 3 seal is on the order of 400 to 600 cubic centimeters per hour and the leakoff is diverted into the radwaste system.

2.4 SDS DESIGN

2.4.1 Overview

The No. 1 RCP seals are sensitive to water temperature, such that within minutes of losing all seal cooling, the seal may depart from nominal conditions and approach leak rates in excess of 20 gpm (Reference 5). The combined leakage from all RCP seals is a significant contributor to inventory loss during a loss of all seal cooling (LOASC) event and could lead to uncovering of the core and fuel damage. The SDS is designed to limit seal leakage during a LOASC event to reduce reactor coolant inventory loss as well as limit the number and complexity of operator actions required for responding to the event. This improves the reliability and robustness of the response to a LOASC event.

The SDS is a passive, mechanical shaft sealing system that can be installed into existing Westinghouse RCPs. The SDS is passively actuated by elevated fluid temperatures on the low-pressure side of the No. 1 RCP seal. Once this seal is actuated, it will limit RCP shaft leakage to less than 1 gpm during LOASC events. It also does not impact, in any way, natural circulation flow within the RCS[1]. The SDS is a one-time use seal and must be replaced after actuation. The design life of the SDS is 9 years.

2.4.2 Design Basis: Loss of All Seal Cooling

The SDS is designed to passively limit the loss of reactor coolant through the RCP seals during LOASC scenarios. The following parameters define the basic design basis for the No. 1 seal and SDS:

- Design conditions for No. 1 seal in normal operation
  - Seal leakoff temperature: 190°F with short-duration excursions to 235°F
  - Seal normal leakoff flow rate: 1.0–5.0 gpm
  - RCS pressure: 2,250 psia (nominally <50 psia at SDS)
  - Design life: 9 years
  - Cumulative radiation exposure: 350 krads

1. The calculated torque imparted on the impeller from natural circulation is 45 foot-pounds. The minimum breakaway torque required to initiate rotation, as evaluated from 200–2,500 psia, is 240 foot-pounds. These calculations are representative of a 93A pump and are considered representative of all pump models.

- Design conditions for SDS in accident operation
  - RCS cold leg temperature: 571°F with cooldown to 300°F
  - RCS pressure: 2,500 psia with depressurization to 300 psia
  - Maximum seal leak rate: 1.0 gpm
  - Design life: 168 hours

2.4.3 Overview of the SDS Design (All Generations)

The SDS limits leakage through the RCP seals by obstructing the annular flow path between the shaft and the No. 1 seal insert (this flow path is shown in red on Figure 2.4-1).

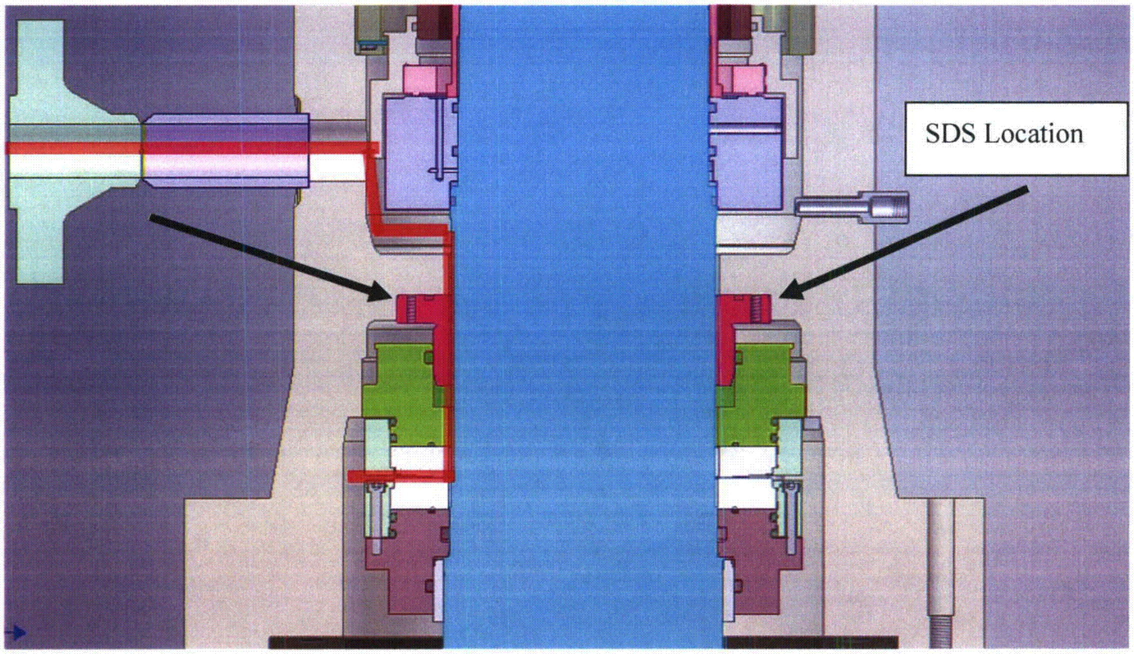

Figure 2.4-1 Location of the SDS

The SDS is located between the No. 1 and No. 2 seals, just upstream of the No. 1 seal leakoff line, as shown in Figure 2.4-1. The seal is located within the existing cross section of the No.1 insert and encircles the shaft. The No.1 seal insert is modified by machining out a portion of the inside diameter (ID) at the top flange. Until actuated, 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 leakoff through the No. 1 seal is unimpeded on its way to the No. 1 seal leakoff line. The No. 1 seal leakoff flow is not affected during normal operation of the rotating equipment.

The SDS is composed of a passive retractable spacer and a series of stacked rings comprising a wave spring, piston ring, polymer ring, and retaining ring, as shown in Figure 2.4-2. The actuating device holds the piston ring "open," permitting No. 1 seal leakoff to flow up the shaft to the No. 1 seal leakoff line. The polymer ring is sandwiched between the piston ring and the retaining ring. The retaining ring is shrink-fitted and retains all 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 spring is designed to maintain contact between the three rings.

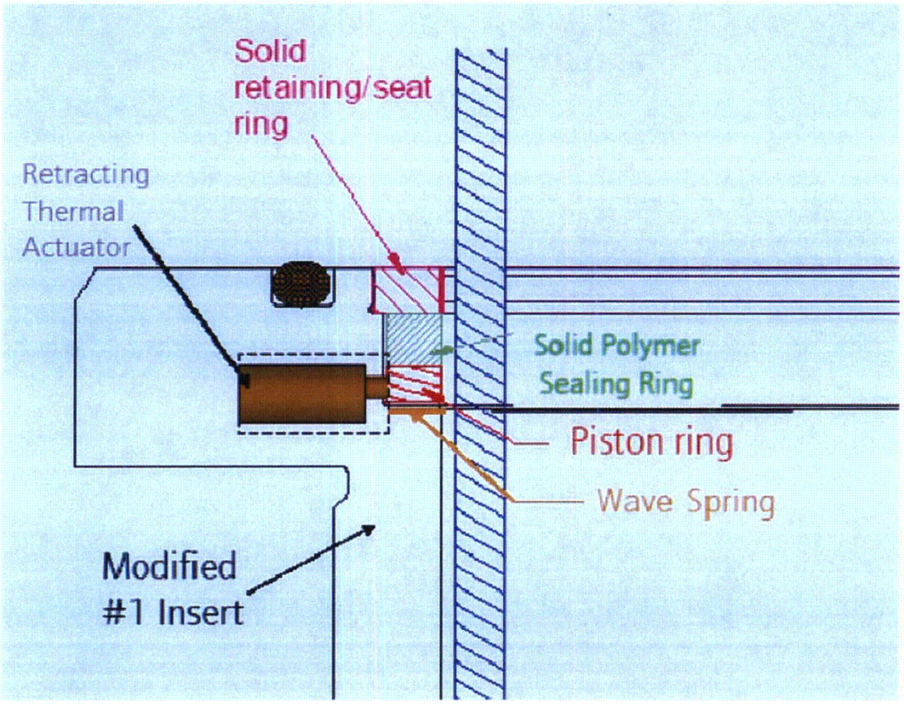

Figure 2.4-2 SDS Internal Components

As is described in Section 3, if both seal injection water and TBHX cooling are simultaneously terminated, hot water from the RCS will begin to migrate upward through the thermal barrier into the seal package. When the fluid coming through the No.1 seal increases to the temperature that causes the passive actuator to retract, the spacer is pulled from between the butt ends of the piston ring. Due to residual stresses, the piston ring snaps closed against the shaft, providing a significant flow restriction and causing the pressure to build on the outside diameter (OD) and bottom face of the polymer ring.

This initial deployment of the piston ring restricts the RCP No. 1 seal leakoff flow, which causes the pressure on the low-pressure side of the No. 1 seal to rapidly increase. The rapidly increasing pressure creates a differential pressure between the outside and IDs of the polymer ring, which eventually causes it to collapse radially and constrict around the pump shaft. 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.

Once the polymer ring is seated on the shaft, the RCP No. 1 seal leakoff flow rate is almost entirely restricted. When backpressure acting on the No. 1 seal approaches the RCS pressure, the fluid film between the faceplates collapses, and the faceplates close. At this point, SDS actuation is complete.

2.4.3.1 Component Descriptions

2.4.3.1.1 SDS Insert

The SDS is contained entirely within a modified No. 1 RCP seal package insert. The insert is modified by adding a counterbore, into which the wave spring, piston ring, polymer ring, and retaining ring are seated. Additionally, one radial hole is bored into the flange of the insert to accept the thermal actuator (Figure 2.4-2). The insert is modified to maintain the original design clearance between the insert ID and the shaft or shaft sleeve OD. As such, installation of the SDS does not reduce the radial clearance inside the seal package.

2.4.3.1.2 Wave Spring

The wave spring provides a constant, axial force to maintain constant contact between the faces of the wave spring, piston ring, polymer ring, and retaining ring. [

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2.4.3.1.3 Piston Ring

The purpose of the piston ring is to create the initial pressure differential that is needed to constrict the primary polymer sealing ring around the shaft. The piston ring is a "normally closed" split ring with ordinary butt ends. For Model 93A RCPs, the piston ring seals against a shaft sleeve that has an OD with a specified tolerance to match the "closed" piston ring ID at the actuation temperature. For the remaining applicable models of pumps used in U.S. nuclear plants (93 and 93A-1), the piston ring will seat directly against the pump shaft, which was not manufactured with an adequate tolerance to accept a single size of piston ring. For those pumps, a series of piston rings is provided along with each SDS during first-time installation; one of which must be chosen based on the as-measured diameter of the pump shaft. The SDS installation procedure requires that the shaft diameter, surface finish, and any surface defects be measured and found to be within the SDS design limits prior to installation. It should be noted that the surface finish requirement is unchanged from that of original manufacture.

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Figure 2.4-3 [ ]a,c

2.4.3.1.4 Polymer Sealing Ring

The primary sealing ring is made of polyether ether ketone (PEEK), which is a tough, high-temperature, semi-crystalline thermoplastic offering a favorable combination of mechanical, thermal, chemical, and electrical properties. After the piston ring snaps onto the shaft, the restricted flow path generates a large differential pressure between the outside and IDs of the polymer ring. The imposed differential pressure is large enough to cause the polymer ring to deform radially to the extent that the inside surface of the ring will seat on the shaft. In this condition, the upper face is seated against the bottom face of the retaining ring, and the annular flow path between the shaft and SDS insert is completely isolated.

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2.4.3.1.5 Retaining Ring

The retaining ring fits into the SDS insert with an interference fit, where it establishes and maintains the axial position of the polymer ring, piston ring, and wave spring. [

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2.4.3.1.6 Actuator

Actuation of the SDS is accomplished by withdrawing the spacer from between the butt ends of the piston ring. The spacer is connected to a passive thermal actuator that generates a linear, radial force when heated above a specified temperature [ ]a,c. The axis of the thermal actuator is located perpendicularly relative to that of the shaft and is recessed into the housing of the SDS insert. It is located in a bore made in the flange of the SDS insert.

2.4.3.1.7 O-Rings

The Westinghouse high-temperature O-rings are qualified for service in loss of seal cooling scenarios. The original qualification was completed in the late 1980s and is documented in Supplement 1 to WCAP-10541 (Reference 6). 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.

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2.5 PUMP MODEL AND SEAL CONFIGURATION FOR TESTING AND ANALYSIS BASIS (ALL SDS GENERATIONS)

The operation of the mechanical seal assemblies manufactured by Westinghouse for use in Westinghouse RCPs is consistent among Model 93, 93A, and 93A-1 RCPs. While the RCPs for each of these models may appear to be significantly different, the design of the seal assemblies is similar. From the perspective of the SDS, the primary difference between RCP Model 93A and the other pump models is the sealing surface. The Model 93A SDS seals against a shaft sleeve, whereas for the other pump models, the SDS seals against the shaft. The shaft sleeve is an integral part of the Model 93A RCP mechanical seal assembly as it is currently used without the SDS. This results in the following key differences between the Model 93A SDS and the SDS for the other pump models:

- A new shaft sleeve for RCP Model 93A is provided with the SDS for the first installation of the unit. The diameter, roundness, and finish of the sleeve in the region of the SDS will be tightly controlled to provide a superior sealing surface.

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The SDS design for the Model 93A-1 uses all the same components as the SDS design for the RCP Model 93A with the exception of the piston ring. [

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While testing without failure was achieved for each SDS configuration as described above, for statistical analysis relative to endurance testing, only the Model 93A-1 polymer ring endurance testing was credited, as it represents the most challenging sealing condition among the pump models described.

3 IMPACT TO PLANT SAFETY POSED BY LOSS OF ALL SEAL COOLING

3.1 LOSS OF ALL SEAL COOLING

As established in Section 2, both means of seal cooling require a continuous supply of ac power. The charging pumps supply the seal injection flow and the TBHX is cooled with CCW. In an ELAP event, both of these functions are lost. The following describes the behavior of the three seals if ELAP and LOASC occur. This section provides a summary of the detailed analyses and tests that are documented in WCAP-10541, Revision 2 (Reference 4).

3.1.1 No. 1 Seal Behavior

Shortly after the initiation of a LOASC event, the RCP will be tripped, either as a result of loss of AC power or through required operator action, and will begin a coastdown over a period of approximately 3 to 4 minutes. Water passing through the No. 1 seal would initially be the "clean/cool" seal injection water that had been in the shaft annulus above the TBHX just prior to the LOASC.

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 shaft annulus and the No. 1 seal leak rate during normal operation. The lower internal water volume would begin to be purged within several minutes and would be followed by an increase in seal temperature due to the insurge of high-temperature reactor coolant.

As the seal inlet fluid approaches RCS cold leg temperature, an increase in the seal leakage rate is predicted to occur as a result of:

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Expected seal leakage during a LOASC after the hot RCS fluid reaches the RCP seal area is normally >20 gpm (Reference 4). The calculations supporting this value (with all three seals functioning) were independently verified by a NRC consultant, ETEC, and were determined to be conservative. This expected seal performance is supported by analytical, test, and field service evidence.

3.1.2 No. 2 Seal Behavior

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3.1.3 No. 3 Seal Behavior

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3.1.4 O-Ring Survivability

The non-rotating seal components, such as the O-rings and channel seal, are designed and tested to provide confidence of long-term survivability when in contact with hot reactor coolant fluid as described in WCAP-10541 (Reference 4). The testing regime included exposure to accident pressure and temperature for a prolonged period followed by increasing pressure until failure occurred. The test fixture was designed to simulate the most severe possible extrusion gap for the O-rings. [

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3.1.5 Estimates of RCP Seal Leakage

Estimates of the RCP seal leakage rates for various failures of the RCP seals were developed based on a coupling of the following analyses to determine the overall response:

- Detailed thermal stress analyses of the seal response to the thermal and pressure conditions that are predicted during a LOASC event to determine the mechanical deformations of the seal components under these extreme conditions.

- Detailed thermal-hydraulic analyses of the RCS fluid flow through the seal assembly to determine the flow resistances and effects of two-phase flow through the seal package.

The results of these analyses showed an expected leakage rate in excess of 20 gpm with properly functioning No. 1 and No. 2 seals, a representative leakoff line configuration, and RCS temperature and pressure of 550°F and 2,250 psia, respectively (Reference 5).

4 OPERATING EXPERIENCE

Westinghouse started development of the SDS in 2005. The design evolved between 2005 and 2010, culminating in the installation of the first SDS at Joseph M. Farley Unit 1. A description of the operational experience is provided in the following subsections. A detailed description of the SDS design and operation is provided in Sections 2 (Generation I and II designs) and 5 (Generation III design).

4.1 GENERATION I DESIGN OPERATING EXPERIENCE AT FARLEY

A Generation I SDS was delivered to Farley Unit 1 for installation during the fall 2010 outage. The SDS remained in service until April 2012, when Farley Unit 1 went into its spring 2012 outage.

After being removed from service in April 2012, the SDS was stored at Farley Unit 1 in dry storage before shipping to the Westinghouse Science and Technology Center in May 2012. On July 27, the SDS was installed in the static test machine. The purpose of the test was to slowly increase the injection temperature until SDS actuation occurred. Actuation was expected to occur when the water temperature was between 260°F and 282°F. The temperature was slowly ramped from ambient to 300°F, while the flow rate was maintained at a nominal 1.2 gpm. After reaching 300°F, the SDS did not actuate and the test was terminated.

On the following day, the static actuation test was repeated. The temperature was slowly ramped from ambient to approximately 330°F, while the flow was maintained at a nominal 1.2 gpm. The temperature was maintained at 330°F for several minutes, but the SDS did not actuate and the test was terminated.

After completion of the second failed test, a "stop work" was ordered and an inspection of the failed component commenced.

4.2 GENERATION I DESIGN FAILURE ANALYSIS AND REVISIONS

After the failed actuation of the Farley SDS, it was determined that the actuator did not have enough withdrawal force to pull the spacer out of the piston ring after being subjected to 18 months of at-power conditions and being allowed to dry onsite prior to shipment to Westinghouse for testing and examination.

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Figure 4.2-1 [ ]a,c

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Figure 4.2-2 [ ]a,c

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Figure 4.2-3 [ ]a,c

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4.3 GENERATION II SDS DESIGN OPERATING EXPERIENCE AT BEAVER VALLEY

Two Generation II SDS units were installed in Beaver Valley Unit 2 during the fall 2012 refueling outage. On November 6, 2012, the plant reached full-power operation. On June 1, 2013, after approximately 8 months in service, one of the SDS units was removed from the plant and installed in a shipping container specially designed to allow for the SDS to be transported while remaining immersed in demineralized water. On June 3, 2013, the SDS arrived at the Westinghouse Science and Technology Center for post-operational static actuation testing.

The Beaver Valley Unit 2 SDS was installed in the static tester on June 13, 2013. The purpose of the test was to slowly increase the injection temperature until SDS actuation occurred. Actuation was expected to occur when the water temperature was between 260°F and 282°F. The temperature was slowly ramped from ambient to 300°F, while the flow rate was maintained at a nominal 1.2 gpm. After reaching 300°F, the SDS did not actuate and the test was terminated.

On the following day, the static actuation test was repeated. The temperature was slowly ramped from ambient to 320°F, while the flow was maintained at a nominal 1.2 gpm. The temperature was maintained at 320°F for 30 minutes, but the SDS did not actuate and the test was terminated.

After completion of the second failed test, a "stop work" was ordered and an RCA was commenced.

4.4 BEAVER VALLEY FAILURE AND RCA RESULTS

Following the Generation II failure, more sophisticated diagnostic tools were available. This allowed for a more comprehensive RCA to be performed. [

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Figure 4.4-1 [ ]a,c

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Figure 4.4-2 [ ]a,c

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4.4.4 Takeaways from the RCA

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4.5 PROPERLY FUNCTIONING COMPONENTS

Although the Generation I and Generation II units failed to actuate during post-operational testing, inspections of the individual components revealed that, aside from the retracting actuator, the components performed as designed. The following subsections describe each of the SDS components that demonstrated acceptable behavior following the operational experiences in Generation I and II actuators.

4.5.1 Polymer Ring

After removal from service, both the Generation I and Generation II units were found to have a thin oxide layer on their inside surfaces. The deposits were red in color and were similar in appearance to those that have been observed on other seal components after removal from service. Despite the oxide layer, the polymer rings were in "like-new" condition, free from any surface defects, wear marks, or other deficiencies. After disassembling and inspecting the Generation I SDS, the components were reassembled and the seal was successfully actuated in the static test machine. While inspecting the Generation II SDS, a special tool was used to carefully spread the ends of the piston ring to determine if any bonding had occurred between the piston ring and retracting actuator spacer. During this test, the piston ring was observed to be free to move with respect to the polymer ring, indicating that no bonding had formed between the surfaces of the polymer ring and piston ring. In all other aspects, the condition of the Generation II polymer ring was the same as the Generation I polymer ring.

The post-failure inspections of the Generation I and II SDS polymer rings revealed that, for the durations that the seals were in service, the polymer rings were not adversely affected by radiation, chemistry, or any other environmental condition that would have prevented the rings from actuating and sealing. After reassembling the actuator, the seal was tested and provided an acceptable seal in the static test rig.

4.5.2 Piston Ring

One part of the post-failure inspections of the Generation I and II SDS units was to measure the piston ring closure force. In both cases, the piston ring closure force, measured with the piston ring in the open position, was found to be within the specified limits for a new piston ring [ ]^{a,c}. The measurements demonstrate that, for the durations that the Generation I and II SDS units were installed, the piston ring closure force remained within the acceptable levels. After inspection of the Generation I SDS, the components were reassembled and successfully tested in the static tester, indicating that the piston ring retained an acceptable closure force.

These observations demonstrate that in both the Generation I and II SDS units, the piston ring retained adequate closure force to allow the SDS to function properly (if the retracting actuator had stroked). Additionally, on both seals' piston rings, the surfaces were in good condition and were free from corrosion, scratches, or other indications of wear or degradation.

4.5.3 Wave Spring

Following the operational experience at Beaver Valley and Farley, the wave springs of both SDS units were evaluated and found to be within specification for new parts [ ]^{a,c}. Neither component had significant surface deposition, corrosion, or evidence of wear. After inspecting the Generation I seal, the components were reassembled and successfully actuated and sealed, further demonstrating that the wave spring had not been degraded during its service in the seal package.

4.5.4 Thermal Piston and Thermal Wax

The original-design retracting actuator, which was used in the Generation I SDS and (with minor modification) the Generation II SDS, used a thermal piston to "unlatch" a spring-driven plunger that would pull the spacer from between the butt ends of the piston ring. A sketch of the thermal piston is provided in Figure 4.5-1.

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Figure 4.5-1 [ ]a,c

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In both the Generation I and II SDS units, it was confirmed that the thermal wax had pressurized the chamber and caused the thermal piston to stroke. [

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These inspection results show that both the Generation I and II SDS thermal pistons performed as designed. The wax and O-rings had not been degraded by radiation, chemistry, or other environmental conditions. Although the actuator has been redesigned to eliminate the failure modes that caused the Generation I and II post-operational failures, the new direct-acting actuator relies on the same thermal wax and O-ring materials as the original design. These materials are demonstrated to be suitable for service in the RCS, as well as a reliable means of initiating the SDS actuation sequence.

4.6 DESIGN PROCESS AND QUALITY ASSURANCE

Generation I and II SDS units were qualified and tested using Westinghouse's design and design review process. During the evolution of the SDS development program, several design reviews were successfully completed in accordance with the Westinghouse QMS. Confidence in the process and testing were defensible by the quality of manufacturing and repeatability in laboratory testing results. Every manufactured component was subjected to rigorous manufacturing and quality standards. This also included post-manufacturing acceptance testing of the piston ring as well as post-assembly actuation testing of the retracting actuator. [

]a,c As a result, an emphasis on enhancing the Generation III SDS design process, coupled with a comprehensive extent-of-condition evaluation, was determined to be absolutely essential to conclusively demonstrate reliable actuation and extensive sealing capability.

5 GENERATION III SDS DESIGN IMPROVEMENTS, MANUFACTURING, AND ENHANCED DESIGN PROCESS

5.1 COMPONENT DESIGN IMPROVEMENTS

The lessons learned from the ACA at Farley and the RCA at Beaver Valley Unit 2 led to a number of design improvements. These improvements were aimed at reducing friction, optimizing forces within the SDS assembly, increasing corrosion resistance, eliminating complexity, and increasing margins. Confidence in the performance of the Generation III SDS has been significantly increased through expanded use of design failure modes and effects analysis (DFMEA) and process failure modes and effects analysis (PFMEA)[1], peer reviews, re-evaluated assumptions, and increased customer participation.

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Figure 5.1-1 [ ]a,c

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Figure 5.1-2 [ ]a,c

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5.2 MANUFACTURE AND ASSEMBLY

Each of the SDS components is manufactured or commercially dedicated in accordance with the Westinghouse QMS. In addition to conventional geometric dimensioning and tolerancing, the adequacy of SDS components is controlled by a series of component inspections. Each of the assembly and inspection steps is performed in accordance with a verified procedure. This section is not a comprehensive review of the procedures, but rather serves as a high-level overview.

Critical dimensions of each component are measured and verified to be within the defined manufacturing tolerances. [ ]a,c

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5.3 ENHANCED DESIGN PROCESS

To enhance the design process, an emphasis on process formality, rigor, and discipline was reinforced throughout the organization with a strong focus in the areas of OpE, extent-of-condition, and independence. Specifically within those three areas, the design process has been enhanced to utilize a broader range of organizational expertise, independent third-party and licensee participation, and extent-of-condition evaluations.

In consideration of the OpE, the design committee has been strengthened and broadened specifically within the areas of design process, metallurgy, chemistry, and design engineering. Diversifying the design organization was intentional to support strict adherence to, and discipline in, the design process, as well as to strengthen resources in areas previously determined to be challenged.

Process formality and rigor were further enhanced through the inclusion of an independent third party. A third party, recommended by the licensees, has fully participated in the design process as well as the RCA to provide independence and intentionally challenge assumptions and the thoroughness of the design process. [

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]a,c within the design process increased the depth of OpE of the design committee, ensuring the operating variables of the application had been considered and thoroughly challenged during the design process. Incorporating the plant engineering and OpE into the design process supported a significantly more robust and disciplined process. [

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To further enhance the design process, a comprehensive extent-of-condition evaluation was conducted on all aspects of the mechanical design. This evaluation focused primarily on analysis, which is described in Section 6, to determine the basis for development and qualification testing (Section 7). A strong emphasis on the extent-of-condition evaluation is essential to the thoroughness of a design process and is critical to establishing design credibility.

In summary, the design process has been enhanced by implementing and continuing emphasis on process formality, rigor, and discipline. This has been accomplished by including independent review and stakeholder involvement, and strengthening and expanding the diversity and skill sets of the designers and review committee.

6 ANALYSIS

The redesign effort initiated after the post-operational failures experienced at Beaver Valley and Farley and included an analytical component in which potential risks, performance concerns, and other matters regarding the extent-of-condition were evaluated.

This section provides an overview of the major analyses that were performed or reevaluated in support of the comprehensive Generation III SDS development effort.

6.1 THERMAL-HYDRAULIC ANALYSIS

6.1.1 Background and Purpose

A thermal-hydraulic analysis of the RCP was performed to reevaluate the time to SDS actuation, as well as the flow rate and pump speed at the time of actuation. This calculation was necessary to show that the maximum pump speed at the time of SDS actuation can be tolerated by the SDS components. If the pump speed were to be too high at the moment of actuation, the polymer ring would be damaged and sealing may not occur or the desired reduction in leakage may not be achieved.

This analysis was performed to calculate the maximum possible shaft speed at the time of SDS actuation for each model of pump. Testing was then performed to show that the SDS could survive a coastdown from the maximum possible actuation speed.

6.1.2 Assumptions

Due to the complex nature of No. 1 seal performance, assumptions were made to simplify the problem and add conservative margin to account for uncertainty. "Conservative" in this context refers to the most rigorous conditions for demonstrated survivability of the SDS. The major assumptions inherent in this model are as follows:

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6.1.3 Methodology

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Figure 6.1-1 [ ]a,c

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Figure 6.1-2 [ ]a,c

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Figure 6.1-3 [ ]a,c

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Figure 6.1-4 [ ]a,c

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Figure 6.1-5 [ ]a,c

6.1.4 Results

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Table 6.1-1 [ ]a,c

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6.2 SDS ASSEMBLY KINEMATIC ANALYSIS

6.2.1 Background and Purpose

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The kinematic analysis provides several useful outputs. First, it provides a sensitivity calculation to determine the maximum coefficients of friction between the various components for which the SDS can still function. Additionally, the model calculates the maximum pullout force for the spacer, which can be used to determine if the actuator is capable of providing enough force to withdraw the spacer with an adequate margin.

Based on the outputs from the kinematic analysis, testing was performed to confirm that the SDS is not susceptible to failures due to friction.

6.2.2 Assumptions

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6.2.3 Methodology

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Figure 6.2-1 [ ]a,c

6.2.4 Results

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Table 6.2-1 [ ]a,c

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Figure 6.2-2 [ ]a,c

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6.3 RE-EVALUATION OF POLYMER RING DYNAMIC TEST RESULTS

6.3.1 Background

During the redesign effort, careful consideration was given to dynamic testing performed on the polymer ring. Over the years that the SDS was under development, the behavior of the polymer ring when subjected to shaft rotation has been characterized by several different testing programs. Each of these testing programs offered incremental improvements, because the dynamic testing capabilities expanded based on the lessons learned from prior tests.

Following the RCA of the failed Generation II SDS, a qualitative survey of all dynamic testing was performed and the quality of each test's results was evaluated. This section describes the results of that evaluation.

6.3.2 Results

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6.4 ACTUATOR KINEMATIC ANALYSIS

6.4.1 Background and Purpose

A kinematic analysis of the direct-acting actuator was performed to quantify all of the forces acting on the actuator piston. [

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6.4.2 Assumptions

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6.4.3 Methodology

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Table 6.4-1 [ ]a,c

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6.4.4 Results

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Table 6.4-2 [ ]a,c

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Figure 6.4-1 [ ] [a,c]

7 TESTING

As a result of the post-operational failure of the Generation II SDS, a newly designed product has been developed that builds upon the successes of the original SDS and addresses the deficiencies. As discussed in Section 4, the post-operational failures of the Generation I and II SDS assemblies from Beaver Valley and Farley were related to the actuator design and the interface of the actuator and piston ring. Therefore, some of the qualification tests for non-actuator or non-piston ring components of the earlier generations of SDS are still applicable. This section describes the test results from the Generation I and II SDS that remain applicable as well as the new qualification testing program that was performed for the Generation III SDS.

7.1 PREVIOUS TESTING BEING CREDITED

7.1.1 Polymer Ring Endurance Tests

The endurance tests are intended to demonstrate that the SDS can withstand extended exposure to the limiting design conditions (maximum reactor cold leg temperature/pressure and maximum polymer ring extrusion gap) in LOASC conditions. [

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The endurance test subjected the polymer ring to LOASC conditions for an extended period of time, during which it must maintain leakage at less than 1 gpm. Using a static testing machine (sometimes referred to as an "endurance tester"), the polymer ring was tested repeatedly at the maximum RCS pressure and various temperatures. [

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7.1.2 Polymer Ring Radiation Tests

At the time the SDS was originally designed, Westinghouse had limited OpE with PEEK in the RCS. The academic literature on the radiological stability of PEEK (Reference 7) indicates that the exposures expected at the RCP seals do not produce any significant change in material properties; however, for assurance, Westinghouse conducted prototypical radiation testing on the PEEK from which the polymer sealing ring is manufactured.

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Based on conservatively estimated exposure rates, the radiation testing performed on the PEEK polymer ring demonstrates that the radiation exposures expected in the field do not affect the ability of the SDS to actuate, create a seal, and limit leakage to below 1 gpm. This conclusion is supported by materials testing performed by Westinghouse and industry literature.

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7.1.4 Sealing Surface Condition Testing

Each Model 93A SDS is provided a new shaft sleeve with a tightly controlled sealing diameter. Models 93 and 93A-1 pumps do not have shaft sleeves and the SDS must seat directly against the shaft. [

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Figure 7.1-1 [ ]a,c

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7.1.5 Shaft Sleeve High-Temperature O-Ring Testing

The Model 93A SDS seals against a shaft sleeve, which is located between the No. 1 runner and the No. 2 seal assembly. The sleeve fits over the shaft with a slight clearance fit and flow is prevented from passing behind the sleeve by a high-temperature O-ring. As this flow path represents a possible bypass to the SDS, testing was performed to demonstrate that the sleeve O-ring was capable of withstanding the temperatures and pressure that are expected during a LOASC event.

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Figure 7.1-2 [ ]a,c

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7.1.6 Lower Lower-Bounding ELAP Tests

The polymer ring endurance tests described in Section 7.1.1 and the static actuation tests described in subsection 7.3.2.8 demonstrate the SDS unit's capabilities of actuating, sealing, and maintaining a seal for the upper-bounding (ELAP) conditions (i.e., maximum RCS temperature and maximum RCS pressure). However, these conditions alone do not represent every possible LOASC scenario that may occur in a PWR. To provide reasonable assurance that the SDS is capable of performing its design basis functions in scenarios other than the upper-bounding LOASC, an additional set of test parameters was developed to represent lower-bounding conditions. Between the upper- and lower-bounding scenarios, all postulated LOASC events are represented.

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Table 7.2-1 [ ]a,c

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Table 7.2-4 [ ]a,c

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Table 7.2-5 [ ]a,c

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7.3 QUALIFICATION TESTING FOR GENERATION III SDS

The qualification program for the Generation III SDS represents a significant departure from the testing regimen by which the Generation I and II SDS units were qualified. Whereas the Generation I and II qualification programs individually explored various environmental factors and their potential impacts on SDS performance, the Generation III qualification program was designed to replicate in-service conditions by performing environmental conditioning and performance testing in series. Additionally, the reliability of the Generation III SDS was demonstrated by successful performance in 59 full-scale static actuation tests, all of which were performed with SDS assemblies that had been subjected to the entire sequence of environmental conditions.

Input parameters for the environmental tests were developed based on OpE data from operating PWRs and, where appropriate, have been either scaled by a suitable FS for conservatism or evaluated statistically to demonstrate that the tests are more challenging to SDS performance than any recorded in-service conditions for the entire lifetime of the SDS assembly. In instances for which adequate plant or test data were not available, test input parameters were derived from engineering analysis, which – in every case – was verified to demonstrate conservative margin.

Each of the qualification tests has specific acceptance criteria to be verified before subsequent tests; however, the general logic in developing the test program was to demonstrate that each of the effects under investigation, individually or cumulatively, would neither cause the SDS to actuate inadvertently nor prevent it from actuating if a LOASC event arises.

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Figure 7.3-1 [ ]a,c

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Figure 7.3-3 [ ]a,c

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Figure 7.3-4 [ ]a,c

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Figure 7.3-5 [ ]a,c

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Figure 7.3-7 [ ]a,c

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Figure 7.3-8 [ ]a,c

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Figure 7.3-9 [ ]a,c

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Figure 7.3-11 [ ]a,c

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Figure 7.3-12 [ ]a,c

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Figure 7.3-14 [ ]a,c

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Figure 7.3-15 [ ]a,c

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Figure 7.3-16 [ ]^{a,c}

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Table 7.4-2 [ ]a,c

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Figure 7.4-1 [ ][a,c]

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Table 7.4-9 [ ]a,c

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Figure 7.4-2 [ ]a,c

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Figure 7.4-3 [ ]a,c

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Table 7.4-11 [ ]a,c

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Figure 7.5-1 [ ]a,c

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Table 7.5-1 [ ]a,c

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7.5.1.2 [ ]a,c

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7.5.1.3 [ ]a,c

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Figure 7.5-2 [ ]a,c

7.5.2 [ ]a,c

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Figure 7.5-3 [ ]a,c

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7.5.2.2 [ ]a,c

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Figure 7.5-4 [ ]a,c

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7.5.3 [ ]a,c

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7.5.3.1 [ ]a,c

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7.5.3.2 [ ]a,c

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Figure 7.5-5 [ ]a,c

8 SUMMARY AND CONCLUSIONS

8.1 SUMMARY

The Generation III SDS has a more rigorous and disciplined design process, testing regimen, and philosophy, which yields a robust design with improved and validated design margin. Furthermore, previous OpE can be predicted by our regimented testing and analysis. This adds further confidence that the Generation III SDS will work as intended.

One of the objectives of the Generation III SDS was to understand the extent-of-conditions and design a system robust against beyond-design-basis external events. Unlike previous generations, the criteria for design and testing were determined based on most-limiting estimated corrosion conditions and validated through OpE. Furthermore, key assumptions were validated by internal experts, licensees, and independent third-party consultants. Throughout the design process, an independent consulting firm and licensees fully participated, which included but was not limited to reviewing design calculations and test plans as well as challenging fundamental assumptions. Lastly, complexity was reduced in the device. The new actuator has better performance and considerably fewer failure mechanisms.

Table 8.1-1 illustrates some of the design characteristics and criteria used in the Generation II and Generation III SDS designs. The changes made reflect little, if any, assumption of conditions at actuation. They assume and test for conditions at the extreme ends in the RCS environment.

The Generation III device also passes every test successfully completed by the Generation II device, as well as several additional ones. Moreover, many of these tests are sequential, testing numerous effects on top of each other. This reproduces actual conditions more effectively than separate effects testing and represents the most conservative testing possible. Table 8.1-2 illustrates some of the extensive tests conducted on the Generation III SDS device and how the Generation II device compares. Some tests are new and validate performance against failure mechanisms discovered in the Generation II failure RCA or mechanisms that fit into a beyond-design-basis category.

Table 8.1-1 [ ]^{a,c}

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Table 8.1-2 [ ]a,c

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8.2 CONCLUSIONS

The SDS device now has significant margin exceeding all postulated conditions. The new tests, when compared to the old requirements, clearly illustrate the design failure mechanisms at play in the previous devices. These match the findings of the RCA. As the Generation III device passed all these tests, it should be expected that the newest SDS offering will perform reliably and consistently in the nation's fleet of PWR nuclear power plants.

This conclusion supports the assertion that utilities should be permitted to continue crediting the SDS product in their OIP submittals for FLEX. SDS will reliably actuate under ELAP events, limiting RCS seal leakage to 1 gpm or less.

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10 LIST OF OPEN ITEMS

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APPENDIX A

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APPENDIX B

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APPENDIX C

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APPENDIX D

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