PRESSURIZED WATER REACTOR OWNERS GROUP

PWROG
PWR Owners Group

**PWROG-14001-NP**
**Revision 1**

WESTINGHOUSE NON-PROPRIETARY CLASS 3

# PRA Model for the Generation III Westinghouse Shutdown Seal

## Risk Management Committee

## PA-RMSC-0499R2

**July 2014**

Westinghouse

**PWROG-14001-NP**
**Revision 1**

# PRA Model for the Generation III Westinghouse Shutdown Seal

## PA-RMSC-0499R2

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**July 2014**

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| | Vandellos 2 (W) | X | |
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| | Tihange 1 & 3 (W) | | X |
| Electricite de France | 58 Units | X | |
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## EXECUTIVE SUMMARY

Westinghouse has developed a reactor coolant pump (RCP) SHIELD® Passive Thermal Shutdown Seal (SDS) (Generation III) that restricts reactor coolant system (RCS) inventory losses to very low leak rates during 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 Number 1 seal and the Number 1 seal leak-off line to provide a low leakage seal in the event of a loss of all RCP seal cooling. The installation of the SDS permits plants to respond to a wide range of events with only a turbine-driven or diesel-driven auxiliary feedwater pump available. These events include station blackout, fires that disrupt power supplies, loss of component cooling water system, and loss of service water system. Because there are negligible RCS inventory losses through the RCP seals with the SDS installed, RCS makeup is no longer necessary to achieve a stable state.

The consensus Probabilistic Risk Assessment (PRA) model for performance of Westinghouse RCP seal packages with high-temperature O-rings is the WOG2000 model that has been reviewed and approved by the United States (US) Nuclear Regulatory Commission (NRC) for use in the PRA. Risk-informed applications derived from PRA studies using the WOG2000 model have become an integral aspect of plant operation and include daily plant configuration risk management activities, Mitigating System Performance Index (MSPI) reporting, license amendment requests for changes to the plant Technical Specifications (TS), and regulatory interactions associated with the Significance Determination Process (SDP).

Plants installing the Westinghouse Generation III SDS will likely change their PRA to credit the reduced seal leakage capability of the SDS. The new SDS model can be appended to the current WOG2000 model or other future seal leakage models in the PRA. In order to most efficiently utilize both NRC and utility resources in reviewing PRA models used in risk-informed applications, the PRA model for the SDS is being submitted to the NRC for review and approval.

The performance of the SDS has been verified by testing and analysis. The testing has included individual component tests as well as tests of the entire seal assembly under conditions that exceed those observed in RCP seal operating experience.

The PRA model developed for the Generation III SDS is based on the extensive testing and analysis performed on the Generation III SDS design. Integration of the Generation III SDS into the plant PRA model may result in a significant decrease in core damage frequency (CDF). 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 CDF risk metric, the installation of the SDS may also permit licensees to modify their coping strategies for station blackout and fires as required by 10 CFR 50.63 and 10 CFR 50.48, respectively, by assuming an RCP seal leak rate of 1 gpm per RCP for the duration of the event. A deterministic model of SDS performance is included for information, but no NRC review or approval of the deterministic model is requested.

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## RECORD OF REVISIONS

| Revision | Date | Revision Description |
|---|---|---|
| 0 | June 2014 | Original Issue |
| 1 | July 2014 | Added clarification of the relation between the WOG2000 model, future seal models, and the SDS PRA model. Clarified limitations and applicability of the WOG2000 model. Provided additional details of the leak rate calculations in Section 2.3.2. |

## ACRONYMS

| | |
|---|---|
| ac | Alternating Current |
| CDF | Core Damage Frequency |
| ELAP | Extended Loss of ac Power |
| gpm | Gallons per Minute |
| MSPI | Mitigating Systems Performance Index |
| NRC | Nuclear Regulatory Commission |
| PRA | Probabilistic Risk Assessment |
| psia | Pounds per Square Inch Absolute |
| psig | Pounds per Square Inch Gage |
| PWR | Pressurized Water Reactor |
| RCP | Reactor Coolant Pump |
| RCS | Reactor Coolant System |
| rpm | Revolutions per Minute |
| SDP | Significance Determination Process |
| SDS | Shutdown Seal |
| TS | Technical Specifications |
| US | United States |

# 1 INTRODUCTION AND PURPOSE

## 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 RCPs may continue to run to provide forced circulation between the core and steam generators for decay heat removal. The Westinghouse RCP seal package consists of a series of three seals which provide a barrier to limit leakage of the reactor coolant system (RCS) fluid. The design includes redundant seal cooling functions, which maintain the controlled leakage to within allowable values. Cooling to the RCP seals is provided by seal injection with thermal barrier cooling available as a backup. RCP cooling by either means alone is sufficient to provide adequate seal cooling so that prompt mitigating actions are not required.

As long as cooling is provided to the RCP seals by either means, the seals function normally and there are no significant RCS inventory losses. If seal injection flow is provided, the flow through the seal package (between 1 and 5 gallons per minute (gpm) per RCP) comes from seal injection (nominally 8 gpm per RCP) with the excess seal injection traveling down the RCP shaft and into the RCS. If seal injection is lost, but thermal barrier cooling is available, the coolant leakage from the RCS into the seal package is cooled so that the leak rate is controlled at the pre-event seal leak rate (between 1 and 5 gpm per RCP), which does not present a significant challenge to core cooling. If all seal cooling is lost, the leakage of reactor coolant through the RCP seals increases as described in WCAP-10541 (Reference 1). Loss of RCS inventory, by means of the RCP seal leakage after a loss of all seal cooling, can result in loss of core cooling if mitigating actions are not completed in a timely manner.

For plants with Westinghouse RCPs, compliance with several of the United States (US) Nuclear Regulatory Commission's (NRC) regulatory requirements is impacted by the performance of the RCP seals when all RCP seal cooling is lost. Most notable of these are the station blackout coping strategies for compliance with 10 CFR 50.63 and the fire coping strategies for compliance with 10 CFR 50.48.

The probabilistic risk assessments (PRAs) for plants with Westinghouse RCPs 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 hazard initiating events including fire initiating events and external hazard initiating events such as seismic, external flooding and high winds. A PRA model for Westinghouse RCP seal behavior under loss of all seal cooling conditions, commonly referred to as the WOG2000 model, is provided in WCAP-15603 (Reference 2).

To provide a means for utilities to address potentially risk-significant events, Westinghouse has developed an RCP Shutdown Seal (SDS), the Generation III SHIELD® Passive Thermal Shutdown Seal, which will limit RCS inventory losses to very low leak rates in the event of a loss of seal cooling. The SDS is a thermally actuated, passive device that is integral to the Number 1 seal insert and is located between the Number 1 seal and the Number 1 seal leak-off line to limit

RCS inventory losses in the event of a loss of all RCP seal cooling. The PRA model for the Generation III SDS can be appended to the current WOG2000 model in plant-specific PRAs. The construction of the model also allows it to be appended to any future PRA models of RCP seal leakage that may be developed to replace the WOG2000 model.

A detailed description of the Generation III SDS can be found in TR-FSE-14-1 (Reference 3). TR-FSE-14-1 provides a basis for use of the Generation III SDS in FLEX strategies, and provides detailed information regarding the design of the SDS and associated testing results. The NRC reviewed this technical report and concluded that the Generation III SDS is acceptable for use as a FLEX strategy (Reference 9). Rather than repeating the information discussed in TR-FSE-14-1 in this topical report, data that is relevant to the PRA model is summarized herein, and references are made to TR-FSE-14-1 as a source of more detailed information regarding the design and testing of the Generation III SDS.

The PRA and deterministic models in this report apply to the Generation III SDS design. The PRA and deterministic models described in WCAP-17100-P-A (Reference 7) and WCAP-17100-P Supplement 1 (Reference 8), for the previous SDS designs, are no longer valid since operating experience from those designs has shown that they are not capable of reliable operation in plant environments. Unless otherwise noted, all references to the SDS in this report are referring to the Generation III SDS design.

## 1.2 PURPOSE

This report documents the new models for RCP seal behavior under loss of all seal cooling conditions. The NRC is requested to review and approve the PRA model for the Westinghouse SDS described in this report. A deterministic model for SDS performance is included for information, but NRC review and approval of this model is not requested.

# 2 TECHNICAL EVALUATION

## 2.1 PUMP MODELS AND SUB-MODELS

There are four basic Westinghouse RCP models used in the US: Model 93, Model 93A, Model 93A-1, and Model 100A. All of these pumps have 8 inch (nominal diameter) seals. Internationally, there are additional Westinghouse RCP models. These include Model 100D, which also has an 8 inch (nominal diameter) seal, and Models 63, 70, and 93D, which have 7 inch (nominal diameter) seals. The PRA and deterministic models documented in this report apply to the RCP models used in the US. However, no NRC review and approval is being requested for the RCP models not used in the US.

In addition to the four basic US RCP model designations, Westinghouse RCPs can contain an additional identifier to designate differences in some design aspects. An "S" designation refers to the presence of a spool piece between the reactor pump and the motor that facilitates RCP seal inspection and replacement. In pumps with a spool piece, the RCP motor does not have to be lifted from the pump in order to remove the RCP seal package. The seal package is identical for pumps with or without the spool piece. A "CS" designation refers to a cartridge type Number 2 and Number 3 RCP seal. The Number 2 and Number 3 Cartridge Seals are slightly different in design to allow for easier replacement as an assembly, as opposed to individual components. The remainder of the seal package is identical for pumps with or without the cartridge seal design. In general, the SDS will be identical for all pumps within a basic model designation (i.e., Model 93, Model 93A, Model 93A-1 and Model 100A). Minor differences between the designs of the SDS for different RCP models are described below.

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## 2.2 SUMMARY OF APPLICABLE DATA

TR-FSE-14-1 (Reference 3) provides a detailed description of the Generation III SDS design, its test program, and testing results. Testing data that has particular relevance to the SDS PRA and

deterministic models is summarized in this section. [

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### 2.2.1 Actuation and Initial Sealing

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### 2.2.2 Rotating Shaft Sealing

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### 2.2.3 O-Ring Sealing in the RCP Model 93A

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### 2.2.4 Endurance Sealing

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### 2.2.5 Actuation on a Rotating Shaft

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### 2.2.6 Natural Circulation Test Data

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## 2.3 ANALYSIS RESULTS

### 2.3.1 RCP Coast Down and SDS Actuation

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### 2.3.2 Leakage Following Actuation on a Rotating Shaft

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**Figure 2.3-1 SDS Internal Components**

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| Table 2.3-1 Seal Leak Rates with Damaged SDS | | |
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## 2.4 CURRENT PRA MODEL

The current consensus PRA model for Westinghouse RCP seal performance following a loss of all seal cooling is the WOG2000 model described in WCAP-15603 (Reference 2). This PRA model considers various combinations of seal failure scenarios involving the Number 1 and Number 2 RCP seals.

Because the SDS terminates flow before the Number 1 seal leak-off line and before the Number 2 RCP seal, successful actuation of the SDS isolates all of the RCS inventory loss pathways for the normally installed RCP seal package. Therefore, the RCP seal PRA model for plants with an SDS installed would be altered as described in Section 2.5.

## 2.5 PRA MODEL WITH THE SDS

The PRA model for the RCP seals with the SDS must take into account both the probability that the SDS fails to actuate and seal, and the probability that the operators fail to trip the RCPs in a timely manner following a loss of all seal cooling.

### 2.5.1 SDS Failure to Actuate and Seal

Failure probabilities for components modeled in the PRA are commonly developed using Bayesian analysis techniques, which mathematically combine prior information about an event with other data. The prior distribution represents all that is known or assumed about the failure probability prior to collecting any data. As reported in NUREG/CR-6823 (Reference 4), the information summarized by the prior distribution can be objective, subjective, or both. Operational data and data from a previous but comparable experiment could be used as objective data. Subjective information could involve personal experience and opinions, expert judgment, or design information. One class of prior distributions that is widely used is termed noninformative priors, also referred to as priors of ignorance, or reference priors. These names refer to the situation where very little *a priori* information about a parameter is available in comparison to the information expected to be provided by the data sample.

The Jeffreys noninformative prior distribution is commonly used to estimate the failure probability for rare events.

For demand failures, the Jeffreys noninformative mean for beta distributions is given in NUREG/CR-6928 (Reference 5) by:

$$P = \frac{n+0.5}{D+1}$$

Where:

P = Jeffreys noninformative mean
n = the number of failures
D = the number of tests

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For time-dependent failures, the Jeffreys noninformative mean for gamma distributions is given in NUREG/CR-6928 (Reference 5) by:

$$\lambda = \frac{n + 0.5}{T}$$

Where:

$\lambda$ = Jeffreys noninformative mean
n = the number of failures
T = the number of hours

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NUREG/CR-6823 (Reference 4) provides the information necessary to calculate the variances associated with the Jeffreys noninformative prior distributions used to estimate the failure probabilities for the SDS.

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The fault tree structure for assessing the failure probability of the SDS in the PRA model is shown in Figure 2.5-1. A calculated probability for failure of the SDS to seal is included based on a typical PRA mission time of 24 hours. [

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**Figure 2.5-1 Fault Tree for Failure of the SDS (24 Hour Mission Time)**

## 2.5.2 Operator Action to Trip the RCPs

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| Table 2.5-1 Operator Action Times to Trip RCPs Following Loss of Seal Cooling | | |
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| Table 2.5-2 [ ]a,c | |
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## 2.5.3 PRA Model Implementation

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Figure 2.5-2 PRA Model for Loss of Seal Cooling with SDS and the WOG2000 Model

### 2.5.4 Discussion of Uncertainties

The ASME/ANS PRA Standard (References 6 and 10) requires that PRA model uncertainties be identified and characterized so that they may be investigated in the course of risk-informed decision making. Guidance for the treatment of uncertainty in the PRA model and applications is included in NUREG-1855 (Reference 11). Uncertainties that are relevant to the PRA model for the SDS are described below.

#### 2.5.4.1 Parametric Uncertainties

PRA models for the SDS should consider both aleatory (parameter) and modeling uncertainty. Parametric uncertainties refer to the uncertainty in the values for the failure probabilities used in the PRA model. As discussed in Section 2.5.1, [

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#### 2.5.4.2 Performance Uncertainties

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#### 2.5.4.3 Material Uncertainties

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#### 2.5.4.4 Other Modeling Uncertainties

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## 2.5.5 Additional PRA Modeling Considerations

### 2.5.5.1 Level 2 PRA

Core damage accident sequences for various initiating events in existing Level 1 PRAs may be binned as low pressure core damage sequences for consideration in the Level 2 PRA as a result of RCP seal leakage. Consideration of the thermal-hydraulic response of the plant for core damage accident sequences with successful actuation of the SDS may result in these accident sequences being re-binned as high pressure core damage sequences. An assessment of the binning of the Level 1 core damage sequences is required when installation of the SDS is credited in the plant-specific PRA.

### 2.5.5.2 RCS Cooldown and Depressurization

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#### 2.5.5.3 Seal Survivability Assessments

The mechanical seal packages installed in Westinghouse RCPs can be procured from multiple vendors. Therefore, licensees with Westinghouse RCPs that have procured mechanical seals and high temperature O-rings from other vendors should verify that the assessments of Westinghouse O-ring and mechanical seal survivability provided in this report are applicable to the behavior of their seal packages following a loss of seal cooling prior to using those assessments as a basis for RCP seal behavior in the PRA.

#### 2.5.5.4 Common Cause Failures

TR-FSE-14-1 (Reference 3) documents the extensive testing and analysis performed to ensure functionality of the SDS and discusses quality assurance processes that govern its manufacture. [

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#### 2.5.5.5 Operator Action for Tripping RCPs

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#### 2.5.5.6 Inadvertent Actuation

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## 2.6 DETERMINISTIC MODEL

The current model used in deterministic analyses for RCP seal performance following a loss of all RCP seal cooling is based on WCAP-10541 (Reference 1). This model is used in determining the acceptability of coping strategies for 10 CFR 50.48(a) and 50.48(b) (fire protection) and 10 CFR 50.63 (station blackout).

For plants installing the SDS, the fire protection and station blackout analyses can be changed to model a 1 gpm per RCP leak rate, consistent with the design specification and testing for the SDS, provided that the scenario under consideration is within the SDS design specification and qualification testing. [

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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. [

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# 3 LIMITATIONS

The limitations of the Generation III SDS PRA model described in this report are:

- The SDS must be installed in all RCPs in the plant.
- The plant's RCP seals are manufactured by Westinghouse and constructed of silicon nitride to ensure the following:
  - Westinghouse survivability assessments and testing of the O-rings in the seal package are valid.
  - If the plant's RCP seals are not manufactured by Westinghouse, a basis for the use of the SDS model in the PRA should be developed by the licensee.
  - Licensees must confirm that the flow rates in the WOG2000 model are appropriate for use in their plant-specific PRA model, or develop the appropriate plant-specific flow rates.
- The RCP oil lift pumps should not be in operation after RCP startup (the analysis of RCP coast down discussed in Section 2.3.1 assumes that the oil lift pumps are secured).
- The assumed environmental conditions for the SDS for any accident or transient, for which the SDS is credited as a reliable means of controlling the RCS inventory loss through the RCP seals to less than 1 gpm per RCP, are within the limiting analysis, qualification, and testing parameters for the SDS documented in TR-FSE-14-1 (Reference 3).
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The limitations of the Generation III SDS deterministic model described in this report are:

- The SDS must be installed in all RCPs in the plant.
- The RCP oil lift pumps should not be in operation after RCP startup (the analysis of RCP coast down discussed in Section 2.3.1 assumes that the oil lift pumps are secured).
- The assumed environmental conditions for the SDS for any accident or transient, for which the SDS is credited as a reliable means of controlling the RCS inventory loss through the RCP seals to less than 1 gpm per RCP, are within the limiting analysis, qualification, and testing parameters for the SDS documented in TR-FSE-14-1 (Reference 3).
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# 4 SUMMARY AND CONCLUSIONS

Westinghouse has developed an RCP SDS that restricts reactor coolant system inventory losses to very low leak rates when a plant event results in the loss of all RCP seal cooling. The SDS is a thermally actuated, passive device that is installed between the Number 1 seal and the Number 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 a turbine-driven or diesel-driven auxiliary feedwater pump available. The possible events include station blackout and ELAP, fires that disrupt power supplies, loss of component cooling water system, and loss of service water system.

The consensus PRA model for Westinghouse RCP seal performance is the WOG2000 model, which has been approved by the US NRC. The new SDS model can be appended to the current WOG2000 model or other future seal leakage models in the PRA. Plants installing the Westinghouse SDS will likely change their PRA to credit the reduced seal leakage capability of the SDS. In order to most efficiency utilize NRC and utility resources in reviewing PRA models used for risk-informed applications, the PRA model for the SDS is being submitted to the NRC for review and approval.

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 observed in RCP seal operating experience.

The PRA model developed for the SDS is based on the extensive testing and analysis performed on the SDS design. Integration of the SDS within the plant PRA model may result in a significant decrease in core damage frequency (CDF). 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 PRA risk metrics, the installation of the SDS may also permit licensees to modify their coping strategies for station blackout and fires as required by 10 CFR 50.63 and 10 CFR 50.48, respectively, by assuming an RCP seal leak rate of 1 gpm per RCP for the duration of the event.

Both the deterministic and the PRA models for the SDS are applicable for a time period of up to 168 hours at nominal hot standby conditions and are also applicable to any scenario that includes operator actions for RCS cooldown and depressurization.

# 5 REFERENCES

1. WCAP-10541, Revision 2, "Reactor Coolant Pump Seal Performance Following a Loss of All AC Power," Westinghouse Electric Company, November 1986.

2. WCAP-15603, Revision 1-A, "WOG 2000 Reactor Coolant Pump Seal Leakage Model for Westinghouse PWRs," Westinghouse Electric Company, June 2003.

3. TR-FSE-14-1-P, Revision 1, "Use of Westinghouse SHIELD® Passive Shutdown Seal for FLEX Strategies," March 2014.

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